

**Software Defined Radio:
A System Engineering View of Platform Architecture and Market Diffusion**

by

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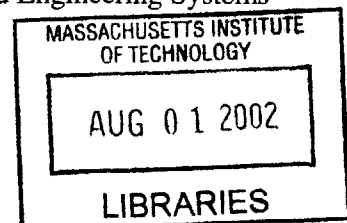
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ABSTRACT

As complexity and ambiguity in products and customer needs increase, existing companies are being forced toward new organizational models. New products require integrating knowledge across technologies, architectures, and functions in new ways, building product platforms that can adapt to changes in markets and product design throughout the product development process. In particular, the wireless telecommunications industry is plagued by multiple incompatible dominant second-generation standards, with each with separate migration paths to future third generation functionality. The high initial investments in spectrum and infrastructure, and corresponding switching costs, call out for a technological solution that can both evolve with the rapid advances in technology and potentially operates seamlessly across multiple incompatible networks to unify a highly fragmented system. In a system engineering context, this thesis investigates the use of software define radio technology (SDR) as a potential replacement for hardware solutions to the multiple air interface standard problem.

This thesis investigates the role of product platform architectures in product market diffusion by studying the selection of appropriate system and product architectures, product market diffusion, and the formation of a system dominant design. Using software defined radio (SDR) technology in the wireless telecommunications industry as a case study, the emergence of SDR as a potential replacement for multiple mobile phone standards is investigated. Compared with interim compatibility solutions that combine multiple air interfaces through hardware. SDRs are an emerging technology that promises to combine multiple air-interfaces into a single wireless phone platform through software configuration. Market and organizational disruptions are determined, and how platform architecture concepts can be used to mitigate these disruptions.

The history of the wireless telecommunications industry is presented to highlight the determinants of product and standards success in the wireless industry. The transition between first-generation (1G) wireless, second-generation (2G) wireless, and the interim high data rate second-generation (2.5 G) system currently being rolled out is discussed. Geographical differences in standards acceptance and the role of government policies are discussed. The strong network effects in the industry are illustrated by the late success of GSM technology in the United States market. The mode of technological standard interaction or competition is determined through the use of the Lotka-Volterra model of technological interaction and lessons learned applied to third generation systems. Plans for third generation (3G) wireless are presented, and the various transition paths from 2G to 3G are discussed. The challenges of transitioning between technologies (technological discontinuities) are highlighted through a discussion of the installed base of legacy

equipment. Software defined radio (SDR) technology is presented, and a platform architecture is developed in the context of 3G market penetration. The use of appropriate flexible SDR system architectures in light of rapidly changing technological and market innovations is discussed.

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SECTION 1: INTRODUCTION

Since its inception, the wireless telecommunications industry has been plagued by multiple incompatible standards. The high initial investments in spectrum and infrastructure, and corresponding switching costs, call out for a technological solution that can both evolve with the rapid advances in technology and potentially operate seamlessly across multiple incompatible networks to unify a highly fragmented system.

When the first generation standards evolved into the current second-generation system, different markets evolved separately under the influence of different regulatory policies and legacy system infrastructure. In North America, a single regional first generation standard has evolved into a second-generation system with three competing incompatible standards. In much of the rest of the world led primarily by Western Europe, multiple regional incompatible first generation systems has evolved into a single second generation standard. Complicating matters further, different regions of the world have allocated radio frequency spectrum to different uses. The result is that there are multiple radio frequency bands combined with the multiple modes defined by a corresponding technical standard. This worldwide evolution of cellular standards is investigated and several lessons learned are discussed. In particular, the roll of backward compatibility in the evolution of each regional standard is discussed.

Geographical differences in standards acceptance and the role of government policies are discussed. The strong network effects in the industry are illustrated by the late success of GSM technology in the United States market. Plans for third generation (3G) wireless are presented, and the various transition paths from 2G to 3G are discussed. The challenges of transitioning between technologies (technological discontinuities) are highlighted through a discussion of the installed base of legacy equipment. Software defined radio (SDR) technology is presented, and a platform architecture is developed in the context of 3G market penetration. The use of appropriate flexible SDR system architectures in light of rapidly changing technological and market innovations is discussed. Finally using SDR as an example, how flexible product platform architectures can enable wide innovation diffusion is illustrated, and how this innovative architecture can fit within the wireless industry value chain is presented.

As infrastructure providers contemplate the large infrastructure investment to deploy transitional two- and half-generation (2.5G) and third-generation (3G) technologies, appropriate transitional compatibility technologies must be deployed. These so called “gateway technologies” provide a means for compatibility between otherwise incompatible systems. These technologies can provide a means for transitioning to a new standard, while maintaining compatibility with an existing larger infrastructure. In this context, a user may have a need for a particular function that the new system offers, but has high switching costs or other network effects that require him to maintain compatibility with the existing legacy system. Additionally, a gateway technology could provide a means for incompatible regional dominant standards to be bridged, providing the user with a “world phone”, or a device that enables call routing and roaming worldwide, and in a seamless manner. Furthermore, lessons learned from the evolution of first- to second-generation standards are applied.

Software defined radios (SDRs) can be thought of as such a gateway innovation. However a broader context, or system engineering view, must be taken in order to determine if this technology is needed, technically feasible, cost-effective, and valuable to parties in the value chain. Using software defined radio (SDR) technology in the wireless telecommunications industry as a case study, the emergence of SDR as a potential replacement for multiple mobile phone standards is investigated. Compared with interim compatibility solutions that combine

multiple air interfaces through hardware. SDRs are an emerging technology that promises to combine multiple air-interfaces into a single wireless phone platform through software configuration.

The analysis that follows discusses several aspects of the wireless to determine the dynamics in the wireless industry. The first two sections, sections 2 and 3, present primarily theoretical overview and historical technical information.

In section 2, this thesis commences to highlight a theoretical foundation to analyze the historical and architectural structures that follows. This framework introduces the management and system engineering theory used to analyze the wireless communications industry and the need for a gateway innovation such as software defined radios. In this framework, the concept of a dominant design is introduced and linked to the concept of a discontinuous innovation. Next, a model for diffusion of innovations is presented. A brief theoretical summary of product platforms follows, and then, a theory of path dependence, network effects, and gateway innovations are introduced. The material in this section is not meant to be complete but is to serve as a useful reference to more complete treatment of the material.

Section 3 highlights the wireless industry by presenting historical and forward-looking information regarding the history and future plans for the wireless industry worldwide are then presented. The history of the wireless telecommunications industry is presented to highlight the determinants of standards success in the wireless industry. Since future third generation system include aspects of voice and data communications, the history of both wireless voice and data transmission is presented. Primarily successful regional first-generation (1G) standards are discussed in detail, and some of the major technical characteristics of each are presented. The technical standards for second-generation (2G) systems are discussed. Finally, the technical standards for third-generation (3G) systems and the planned transition path from 2G systems to 3G through an interim capability that has been dubbed 2.5G is presented.

Section 4 presents in detail the transition from 1G wireless to 2G wireless in the major regional markets. Detailed historical subscriber data for 1G and 2G technologies is presented, and discussed within a management of innovation context. Region differences of innovation uptake are highlighted, and the different roles of gateway technologies within various geographic regions are discussed. The role of regional standards is discussed. A set of lessons learned is discussed, and will be applied later to 3G and SDR technology. Finally, a mathematical diffusion model of technological interaction is fit to the historical subscriber data, the mode of competition determined, and lessons drawn upon to apply later to 3G and SDR technology diffusion.

Section 5 highlights the telecommunications system architecture and software defined radios potential niche within it. This section commences by giving a brief introduction and historical overview of SDR technology. Its roots within the military communications research are highlighted. Next, telecommunications system architecture is highlighted and SDRs potential application is discussed. The layered telecommunications architecture is mapped into various applications and infrastructure layers of the SDR platform. A brief discussion of how this layered abstraction can be leveraged to provide increased market diffusion is undertaken. To provide a rounded view, the broad set of enabling technologies is discussed including: signal digitization, digital signal processing power, and multiple RF air-interfaces. Finally, some current hand-held phone operating systems are presented, and it is discussed whether these are competitors or complementary to SDRs.

The first four sections provide historical context and lessons learned in order to provide the context for the analysis in section 6. Section 6 attempts to decompose the features of a group of cellular handsets currently in the market into a set of standard and extra features. A listing and categorization of all available handsets for all worldwide standards are presented. The manufacturers with models supporting each standard are highlighted. The base or standard set of features is highlighted. The emergence of a potential dominant design of cellular handsets is discussed.

Section 7 draws on all the previous sections to discuss the potential diffusion of SDR technology. Drawing upon the previous sections, and economic theory on gateway innovations, path dependence and increasing returns, the wireless industry's network externalities are highlighted. The number of wireless subscribers demonstrates increasing returns, and socio-political forces that determine different standards in different parts of the world shape the network infrastructure. Gateway innovations have been identified in such industries to bridge incompatible systems, especially in the regional context. Additionally, handset diffusion and dominant design elements are highlighted in this section. Finally, drawing on these conclusions, implications for 3G standards and software-defined radios is discussed.

Section 8 is a brief summary of the analysis presented throughout the thesis.

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SECTION 2: THEORETICAL FRAMEWORK

Introduction

This section highlights the conceptual framework referenced in the thesis. Following overviews dominant design theory, diffusion of innovations, and product platform concepts. The study of technological innovations is key to the understanding whether an innovation such as software defined radios will disrupt the market for existing wireless communications platforms by becoming a new dominant design, or a key component of a new dominant design.

Dominant Design Overview

Although used rather loosely in the literature, a dominant design in a product class is the one that wins the allegiance of the marketplace, the one that competitors and innovators must adhere to if they hope to command significant market following. The dominant design usually takes the form of a new product (or set of features) synthesized from individual technological innovations introduced independently in prior product variants.¹ A dominant design embodies the requirements of many classes of users of a particular product, even though it may not meet the needs of a particular class to quite the same extent, as would a customized design.

For each subsystem and linking mechanism, patterns of experimentation, trial and error, or variation led to the emergence (or selection) of a dominant design which led to incremental change in the standardized design which led, in turn, to subsequent discontinuous technological change. Even in simple systems, the closing on a dominant design is a result of social, political, and economic forces of compromise and accommodation. Transitions to dominant designs and the subsequent technological discontinuity are associated with sweeping organizational and industrial changes as seen in the airplane, radio, photography, power, machine tool, and watch industries.² The processes of variation, selection, and retention occur at the subsystem and linkage levels of analysis. Not all subsystems are of equal importance. Some subsystems are central or core to the product, while others are more peripheral. These critical subsystems, or critical problems, shift over time.³

Nelson and Winter coined “natural trajectories” to describe the phenomenon that technologies typically evolve by exploiting latent economies of scale and potential for increased mechanization of operations that were previously done by hand⁴. They maintain that designers of a technology have at every given point in time beliefs about what is technically feasible or worth trying. Thus the development of a technology is very much constrained and directed by the cognitive framework that engineers bring to the development situation. Only when further performance either are blocked or yield diminishing returns do engineers look for fundamentally different design approaches.⁵

Technological paradigm is a multidimensional construct as Dosi uses the concept to refer to a generic technological task, the material technology selected to achieve the task, the physical/chemical properties of the material. He claims there are two origins for new technological paradigms –either designers cannot improve a technology on the existing paradigm and therefore engage in extraordinary problem solving to find a radically new solution for the generic technological task, or scientific breakthroughs may open up new possibilities for achieving the technological task.⁶ Once designers adopt the new paradigm, they focus on incrementally improving the technology along key dimensions identified by the paradigm.

Technological paradigms have a powerful exclusionary effect: they focus the technological imagination and the efforts of engineers as well as the organizations they work for in rather precise directions while they make them “blind” with respect to other technological possibilities.

Industry standards have important effects on industry structure and organizational fates. Prior to the emergence of standard, many smaller firms compete based on product innovation. After the standard, process innovation and associated production investments raise barriers to entry, drive cost-based competition, and shakeout of an industry now dominated by larger firms. These industry dynamics occur at both the component as well as the system levels of analysis.⁷

As viewed by Abernathy and Utterback, dominant designs are turning points that lead an industry to move from a custom-made to a standardized-product manufacturing system.⁸ Dominant designs are viewed as turning points that lead an industry to move from a custom-made to a standardized-product manufacturing system. This transition from flexible to specialized production processes is marked by a series of steps. The first step is development of a model that has broad appeal. This design satisfies the needs of a broad class of users; it is not a radical innovation but rather a creative synthesis of innovations that were introduced in earlier products. This dominant design attracts significant market share and forces other competitors to imitate this dominant configuration. After the dominant design is in place, subsequent innovations focus on incrementally changing the product; innovations become more cumulative and competition moves from product differentiation to price. Economies of scale are not a mechanism that drives convergence to a dominant design. Rather the emergence of the best compromise makes it possible to sell the product to many different users: economies of scale are relevant after a dominant design is in place.⁹

A dominant design does not embody the most extreme performance in a product class. It is a satisfier of many in terms of the interplay of technical possibilities and market choices, instead of an optimizer for a few. A dominant design reduces the number of performance requirements to be met by a product by making many of those requirements implicit in the design itself. Industry regulation often has the power to impose a standard and thus define a dominant design.

The way a firm manages communications with its customers may have a significant effect on its ability to impose a dominant design. This is the case of market learning. Staying close to the customer makes it possible for producing firms to observe how their evolving products are actually being used, how they are succeeding or failing to satisfy customer requirements, and how design changes might close the gap between product capabilities and user requirements. Close contact with users during the period of experimentation helps firms determine which product features are truly important to customers. Managing this producer users’ interface may take the form of close ties to “lead users,”¹⁰ user associations, and industry groups. Conversely, Christensen has shown that customers for entrenched products can influence a firm not to change when change is called for, increasing their resistance and vulnerability to technological progress.¹¹

As larger numbers of firms enter a product arena, broadening the range of experimentation and the definition of the product technology, expected greater innovation with corresponding greater technology process and productivity advance. Utterback has shown that the appearance of a dominant design shifts the competitive emphasis in favor of those firms – large or small – that are able to achieve greater skills in process innovation and integration and with more highly developed internal technical and engineering skills.

Overall, the inability to change organizational structure and practices in tandem with the evolution of technology in the industry is a major source of failure. Prior to the appearance of a dominant design, one would expect to see a wave of entering firms with many varied, experimental versions of the product, just as were seen in cases of the typewriter, the personal computer, and the early automobile.¹

A dominant design has the effect of enforcing or encouraging standardization so that production or other complementary economies can be sought and perfected. Effective competition then shifts from innovative approaches to product design and features, to competition based on cost and scale as well as on product performance.

Another view of dominant designs consists of technology cycles, periods of variation (eras of ferment) initiated by technological discontinuities that are closed by the selection out of a dominant design. Dominant designs usher in eras of incremental change that are, in turn, broken by subsequent technological discontinuities, and change that are in turn, broken by subsequent technological discontinuities, and the next cycle of variation, selection, and retention.¹² Dominant designs are then the key transition point between eras of ferment and eras of incremental change. Once a dominant design emerges, uncertainty associated with design approaches vanishes and subsequent technical progress elaborates the selected variant².

Diffusion of Innovations

Markets evolve over their lifecycle, and can be segmented in many different ways. Here we will adopt Roger's market diffusion language. Diffusion theory tries to illuminate the question of who buys a technology or product as it evolves.

Figure 2-1 depicts Roger's market segmentation or the Technology Adoption Life Cycle. In this structure, different categories of adopters differ by, for example, social, economic status (resources, affinity for risk, knowledge, complementary assets, interest in the product). The Technology Adoption Life Cycle underlying thesis is that technology is absorbed into any given community in stages corresponding to the psychological and social profiles of various segments within that community. This process can be thought of as a continuum with definable stages, each associated with a definable group, and each group making up a predictable portion of the whole. The following briefly describe the characteristics of each market segment:

Innovators pursue new technology products aggressively. These are people who are fundamentally committed to new technology on the grounds that, sooner or later, it is bound to improve our lives. They are typically intrigued with new fundamental advances and often make a technology purchase for the pleasure of exploring the new device's properties.

Early Adopters buy into a product early in its lifecycle. However they tend not to be technologists, like the Innovators. Their expectation is that by being first to exploit the new capability they can achieve a dramatic and insurmountable competitive advantage.

The Early Majority make up the bulk of all technology purchases. They are driven by a strong sense of practicality. They are content to wait and see how other people are making out before they buy in themselves.

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The Late Majority share the concerns of the early majority plus they are pessimistic about their ability to gain any value from technology investments and undertake them only under duress, typically because the remaining alternative is to let the rest of the world pass them by.

The laggards, finally, don't want anything to do with new technology. The only time they buy a technological product is when it is buried inside another product they must have.

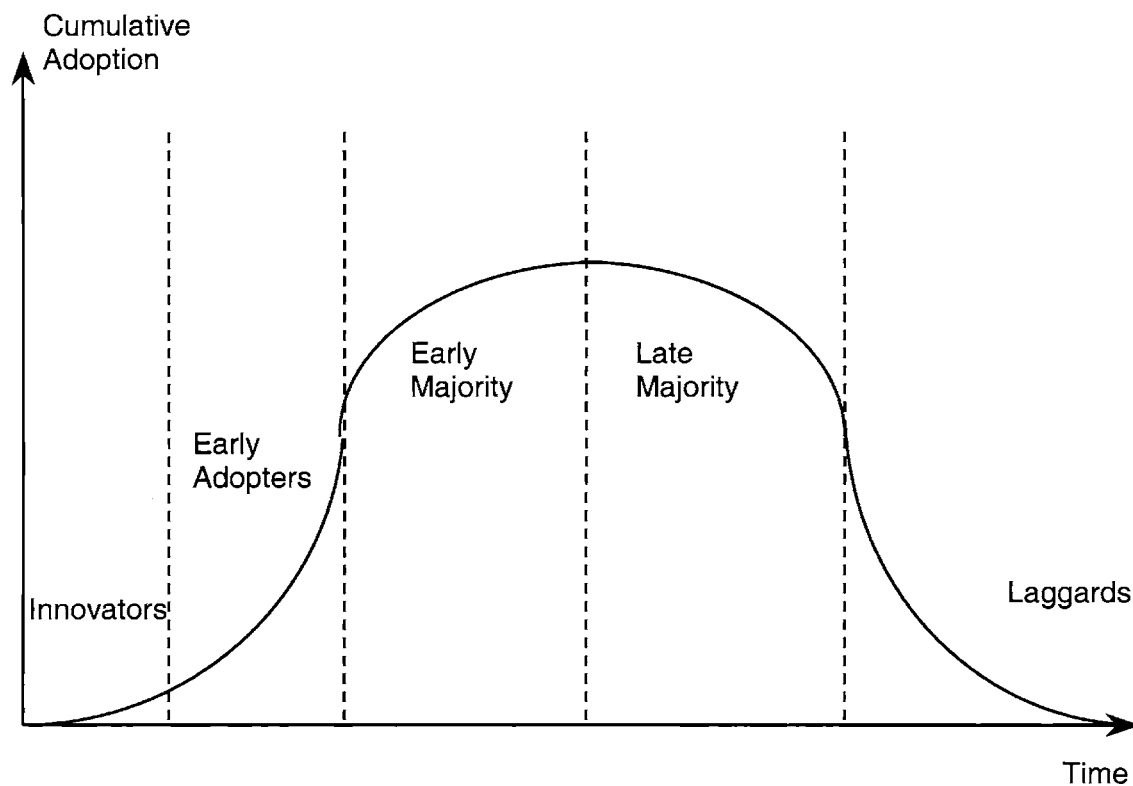


Figure 2-1. Roger's Basic Technology Adoption Life Cycle.¹³

The technology adoption life cycle is a structure where different categories of adopters differ by, for example, social or economic status. The premise is that technology is absorbed into any given community in stages corresponding to the psychological and social profiles of various segments within that community.

Geoffrey Moore builds upon this market segmentation by introducing the concept of a "Chasm" between the Early Adopters and Early Majority.¹⁴ In making the transition from "early adopters" to Early Majority, users often require organizations to develop quite different competencies, for example, services, support capabilities, and more extensive training.

Figure 2-2 attempts to map the various stages of technology or product maturity into tasks required by the market during various stages of the technology life cycle.¹⁵ This framework can be elaborated among many additional dimensions, and this is just meant to illustrate that at different stages in a product's life, a company must adapt a product and supporting services to meet users' needs.

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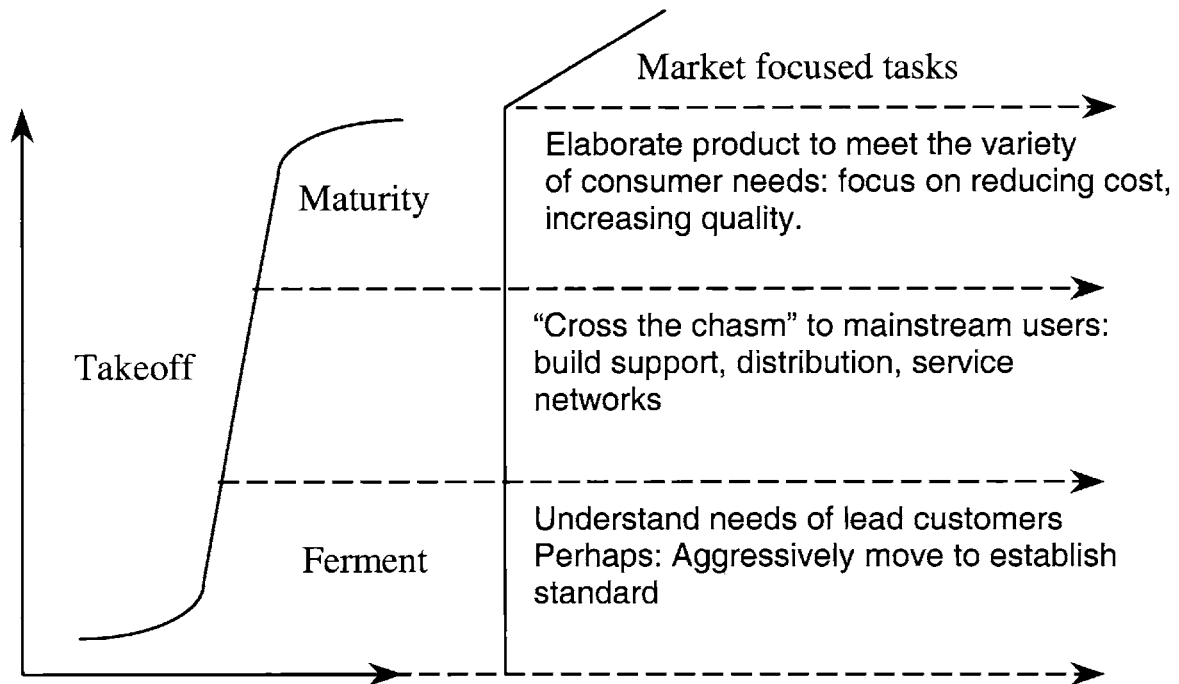


Figure 2-2. Illustration of Market Challenges Over The Technology Life Cycle.¹⁵

This framework is meant to illustrate that at different stages in a products life, a company must adapt a product and supporting services to meet users needs.

At the bottom of the S-curve, during the era of ferment, customer needs are not precisely defined and the market tends to consist of those individuals or firms who have a compelling need for the technology. The advent of the dominant design and the transition to takeoff is triggered by the ability of the innovation to "cross the chasm" to mainstream customers. These customers typically need levels of support and a degree of robustness in the product that early adopters do not, and it is the need to develop these additional skills that is partially responsible for the "chasm" that Moore describes. Another source for the "chasm" is the need to develop positive externalities, largely in the form of an installed base that can act as a reference, to meet the needs of this kind of customer. Christiansen describes the chasm between S-curves¹¹. One might expect trouble between S-curves even if an innovation did not meet different kinds of needs, largely because the type of consumer/customer is likely to differ across different stages. However, Christiansen's work suggests that this problem is further complicated by the fact that most significant innovations in fact meet different combinations of needs.

As a generalization, a consumer will adopt a new technology when the perceived benefit of doing so exceeds the perceived cost. If diffusion occurs, it must therefore be the case that potential consumers differ in some fundamental respects and that either costs are falling over time or benefits are increasing. Table 2-1 provides a framework to discuss the determinants of diffusion, as presented by Rebecca Henderson. This framework is another method to look at the Technology Life Cycle discussed above.

Rodgers' model focuses largely on alternative sources of consumer heterogeneity. In the simplest case -- quadrant 1 - one can interpret it as sorting the population in terms of their closeness to information. In the case of quadrant 2, his model can be thought of as sorting a population in terms of relative benefit. As the innovation diffuses and externalities develop, perceived risk falls or social pressure rises, the innovation is adopted by increasingly marginal consumers. Rodgers focuses

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almost exclusively on consumer heterogeneity as a driver of diffusion since much of the research that he summarizes focused on product diffusion, rather than innovation or technology diffusion. Clearly in reality both sorts of diffusion are important, and therefore it's useful to consider Rodgers as describing only one possible source of heterogeneity.

In general, different kinds of markets tend to be characterized by different adoption dynamics. Giving some thought as to which kind of dynamics are likely to characterize the diffusion of the innovation or technology may yield insight into which kinds of actions are likely to be particularly effective in driving adoption. Relatively simple, low risk innovations that provide significant benefits for nearly everyone (or nearly everyone in the target population) tend to fall into quadrant (1). The name of the game in such markets is, of course, communication, coupled with the attempt to identify those individuals who are central to the communication network in the market. As the differences across consumers grow, and one moves towards quadrant (3), the key task becomes identifying precisely along which dimension consumers differ, or getting a very real sense for the segmentation of the market. In the case of products bought by individual consumers such segmentation may resemble Rodgers', but for industrial goods and for some kinds of consumer products, it may not. In quadrants (2) and (4) these dynamics are supplemented by the forces introduced by change in the technology itself.

Many high technology products fall into quadrant (4). This has important implications for the ways in which they are managed. As both Moore and Christensen suggest, as a technology evolves down a life cycle it is likely to be selling to different kinds of customers -- or, at the very least, to different kinds of needs.¹⁵

The technology:	Consumers are:	
	All the same	Different
Is always the same	Information transfer determines diffusion: The Epidemics model	Diffusion is driven by: Relative risk preferences Social adoption pressure Development of complementary technologies/products Price dynamics Competitive dynamics
Evolves over time	Complicated information transmission dynamics	All of the above <u>plus</u> reductions in cost and increases in benefits due to technical evolution

Table 2-1. Framework for Determinants of Diffusion.¹⁵

This framework is another method to look at the Technology Life Cycle. In general, different kinds of markets tend to be characterized by different adoption dynamics. Giving some thought as to which kind of dynamics are likely to characterize the diffusion of the innovation or technology may yield insight into which kinds of actions are likely to be particularly effective in driving adoption.

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Product Platforms

Developing "platforms" of distinctively different products that share underlying components has been shown to be a faster, cheaper, and better way of getting products to market. Sharing components across a platform of products allows companies to develop differentiated products more efficiently, increase their flexibility, and take market share away from competitors. A product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced.

Good product development means developing a family, or platform of products, and producing them in a flexible process tailored to the needs of individual customers. A platform is the collection of assets that are shared by a set of products. These assets may include components, knowledge, and production processes. Effective platform planning balances the market value of product differentiation against the economies achieved through commonality.

A product can be thought of in both functional and physical terms. The functional elements of a product are the individual operations and transformations that contribute to the overall performance of the product. The physical elements of a product are the parts, components, and subassemblies that ultimately implement the product's functions. The physical elements of a product are typically organized into several major physical building blocks, which are called chunks. Each chunk is then made up of a collection of components that implement the functions of the product. The architecture of a product is the scheme by which functional elements of the product are arranged into physical chunks and by which the chunks interact.¹⁶

A platform is the collection of assets that are shared by a set of products. These assets can be divided into four categories¹⁷:

- Components: the part designs of a product, the fixtures and tools needed to make them, the circuit designs, and the programs burned into programmable chips or stored on disks.
- Processes: the equipment used to make components or to assemble components into products, and the design of the associated production process and supply chain.
- Knowledge: design know-how, technology applications and limitations, production techniques, mathematical models, and testing methods.
- People and relationships: teams, relationships among team members, relationships between the team and the larger organization, and relations with a network of suppliers.

Marc Meyer developed the following thought architecture¹⁸ for product family planning and platforms.

Product family planning and platforms - Companies should plan and manage on the basis of product family, which is a set of products that share common technology and address a related set of market applications.

Simultaneous Design for Production - The design of new products is often constrained by existing capabilities in plant and production equipment. Simultaneous design for production is the early and continuous integration of product design with manufacturing design.

Global Product Design and Market Development - Development teams must assume a global perspective for sourcing technology for new products. Teams should be intimately familiar with market research on customer needs and preferences, distribution channels, support requirements, and technical and product safety requirements beyond domestic borders. Standardization of subsystems is clearly a key part of the global solution.

Discover Latent, Unperceived Customer Needs - New product development must be the ability to intuit, test, and ultimately discover latent, unperceived customer needs. Good market research can identify the perceived needs and preferences of customers. Most companies readily understand how to do this type of research. Far more difficult is the ability to identify needs that customers have not yet learned to articulate.

Elegance in Design - The norm in industry is to add functionality to existing designs. Customers' resistance to complexity is observable even as companies raise the level of complexity in their products. Simplicity is a virtue. And simplicity in product design can often be attained through modular construction. Simplicity, when combined with a richness of features, represents elegance in product design.

Increasing Returns, Path Dependence, Network Effects, and Gateway Innovations

Conventional equilibrium economic theory assumes that the actions of sellers and buyers produce a negative feedback that leads to a predictable equilibrium for prices and market shares. For example, an increase in demand leads to higher oil prices, which encourages conservation (negative feedback on demand) and oil exploration (positive feedback on supply). According to the theory, these feedback processes will bring the market back to an equilibrium in which resources are used most efficiently. However, a market can never be in equilibrium because sellers' supply curves and many consumers' demand functions are constantly changing. Sellers' supply functions change each time they increase the efficiency of some value-adding process¹⁹.

Increasing returns, as developed by Brian Arthur, have the implication that there is a possibility that economic systems may have multiple, rather than unique, equilibria, and that the initial trajectory of an economic system may affect which of the multiple equilibria the system will converge to, namely, path-dependence. Under diminishing returns, static analysis is sufficient: the outcome is unique, insensitive to the order in which choices are made, and insensitive to small events that occur during the formation of the market. Under increasing returns, static analysis is no longer enough. Multiple outcomes are possible, and to understand how one outcome is selected we need to follow step by step the process by which small events cumulate to cause the system to gravitate toward that outcome rather than the others.

Increasing returns properties include²⁰:

- Potential inefficiency, nonpredictability,
- Add inflexibility in that allocations gradually rigidify, or lock-in, in structure, and non-ergodicity, in that small events early on may decide the larger course of structural change.

If one both technologies have increasing returns, but if returns increase at differing rates, one may get locked-in to an inferior technology. The economy, under increasing returns, can dynamically

lock itself in by “small historical events” to a technological path that is neither guaranteed to be efficient, nor easily altered, nor entirely predictable in advance. The most common case is that of technologies chosen for sound engineering reasons at the time but now locked-in by user externalities, denying later, more appropriate technologies a footing. Often technologies are sponsored by firms, like personal computers or video recorders that gain peripheral-product support as their market-share increases, or like the technological networks that offer transportation, communication, or distribution services whose costs decrease with traffic carried.

In the case of competing standards, early adopters are affected by the choices of later adopters, who may or may not fall in with one’s choice and follow suit. New agents will choose partly on the basis of their expectations. Under increasing returns, the outcome becomes path dependent. It is nonergodic - many outcomes are possible, and heterogeneities, small indivisibilities, or chance meetings become magnified by positive feedbacks to “tip” the system into the actual outcome “selected”²⁰.

QWERTY keyboard has become a general example of such lock-ins²¹ that is theorized to occur from switching costs. One is what we might call pure switching costs; the opportunity cost of obtaining, installing and learning to use a new technology. The other form of switching cost is due to “network externalities,” or “external increasing returns”. Normally economic analysis assumes constant or decreasing returns, i.e. that each additional unit of resources devoted to a task brings the same return or less as the last unit. Increasing returns states that a unit of resources $n+1$ has a larger return than unit n . The technology per se is not more efficient when it’s more widely employed --- but it is more valuable. The more common QWERTY keyboards are, the more useful it is to learn them rather than the Dvorak keyboard. In turn, the more people know how the QWERTY layout, the better it is to be selling that, rather than one of its competitors, and the better it is to be buying them for your employees.

In this example, there are increasing returns in the number of QWERTY keyboards in place, and this is due to the value of the network of such keyboards. Leaving that network imposes a switching cost, even if there is absolutely no difference in intrinsic merit between the product and its competitors. Note that the technology with the largest network will, all else being equal, grow at the expense of its rivals, since that is the one with the most valuable network externalities, and hence the highest switching costs to leave.

Depending on the industry, there may be several ways to overcome lock-in. In particular when dealing with systems competing on different standards, the introduction of a gateway technology²² may provide an opportunity to reduce the switching costs. Network technologies are not static, and initial technical incompatibilities between variant formulations of such technologies can have their economic importance mitigated as a result of introduction of a gateway technology. The sponsors of alternative and incompatible technological systems may lack complete control over the course of the rivalry among them, owing to the possibility that other parties, seeking to capture the benefits of network compatibility, may be induced to develop adapter, converter, or translator innovations. Innovations of this sort effectively open “gateways” permitting the technical interconnection of system components that would otherwise remain isolated.

Market rivalries among emerging technologies are not always situations in which technical compatibility between competing systems lies within the exclusive control of the respective system sponsors. It is more likely that there will be private, market-induced responses from third parties. In the power industry, a hybrid system that would integrate elements from the DC and AC electrical supply technologies, each of which had its special area of advantage, elicited the

development of the rotary converter device by an independent inventor-entrepreneur who was not allied with either of the main system sponsors, Edison or Westinghouse.

Once there has been a third party intervention to supply a gateway technology, sponsors of exiting systems have less to gain from trying to develop their proprietary technologies further. Also, once a gateway innovation appears on the scene, even though it is technically neutral in its ability to make use of the competing technologies, its introduction need not be neutral on its impact on the competition between contending variants. It may disturb the delicate balance of market advantages based on the heterogeneity of specialized user-needs, and so assist one particular variant to emerge as the standard for the enlarged network.

Gateway technologies tend to have their own life cycle²². Once they have formed an economically feasible bridge across some technical incompatibility, the passage of traffic over that particular bridge is increased with increasing system usage, thereby directing attention to the cost savings that could be achieved if it were entirely eliminated. For example, once the rotary converter had tipped the balance toward the growth of AC-based electricity supply networks in the United States, the subsequent inducements to eliminate the fixed costs of converter equipment, as well as the costs of energy losses entailed in the conversion itself, acted to focus research and development efforts in the direction of designing end-use equipment, appliances, and motors that were compatible with the dominant form of (alternating) current. Over time, cost and performance characteristics of AC motors tended to improve relative to those of DC motors, until in the United States only users with very specialized needs continued to employ direct current appliances.

Through the effects they have in altering the composition of heterogeneous customers being served by a network, gateway technologies can have indirect consequences for the distribution of eventual network benefits: they may even have effects that prove disadvantageous to the class of customers originally served by a more restricted network.

As will be discussed in subsequent sections of this thesis, wireless technologies are a form of network technologies, and there are several gateway innovations to bridge incompatible standards. Software defined radio technologies can be considered a gateway innovation, with added benefit of further developing the system performance and increasing user benefits.

SECTION 3: WIRELESS INDUSTRY OVERVIEW

Introduction

The global boom in mobile cellular communications has been astounding. At the end of September 2001, there were more than 894 million subscribers around the world, up from just 11 million in 1990. Mobile cellular already accounts for almost one-third of all telephone connections. The subscriber base for wireless communications is growing 15 times faster than the subscriber base for wired services. It seems highly likely that the number of mobile cellular subscribers will surpass conventional fixed lines before 2010²³. Both developed and developing countries are sharing in this revolution: in developed countries, users are flocking to mobile cellular as a complement to existing fixed-lines; in developing nations, mobile cellular is emerging as a substitute for shortages of fixed-lines.

The mobile cellular boom has revolutionized the concept of telephony in a number of ways. First and foremost, with mobile, users no longer call a place but a person. Small, portable handsets have liberated users from the cord that tied telephones to a geographic location, enabling users to be reached anytime, anywhere. Beyond this, compared with fixed telephones, mobile cellular typically offers a greater variety of options in terms of features and tariffs.

Mobile cellular was the first telecommunication market segment where private ownership and competition were introduced in many countries. Foreign, strategic investors almost always back start-up mobile cellular companies²⁴. This combination of competitive markets, private ownership and foreign investment has created an appropriate environment for rapid growth. But the market has been driven, as much as anything, by demand. When mobile phones were first introduced in the early 1980s, they were mainly confined to cars, constrained by weight and power requirements. But as mobile phones became lighter, cheaper and more attractive, they have left the car and entered the briefcase, the handbag and the pocket. A modern portable typically weighs a few ounces, is brightly colored, and has a small screen and more features than the average user might use in a lifetime. Mobile phones have become a fashion accessory. The success of mobile has been a triumph of technology married with marketing.

The vigorous demand for wireless services is fueling intense industrial and government activity, including research and development (R&D) aimed at the quality and reducing costs of wireless technology, design of innovative systems and services, and implementation of new technical standards and policies. This environment is producing diverse wireless technologies and standards, in stark contrast to other areas of communications marked by a convergence toward uniformity. All this activity will ultimately bring the reality close to the vision of "anytime, anywhere" communications.

All aspects of wireless communications are currently subject to rapid change throughout the world. Dimensions of change²⁵ include the following:

- Vigorously expanding demand for wireless products and services;
- Dramatic changes worldwide in government policies regarding industry structure and spectrum management;
- Rapidly advancing technologies in an atmosphere of uncertainty about the relative merits of competing approaches;

- Emergence of a wide variety of new systems for delivering communications services to wireless terminals;
- Profound changes in communications industries as evidenced by an array of mergers, alliances, and spin-offs involving some of the world's largest corporations.

These changes are fueled by opportunities for profit and public benefit as perceived by executives, investors, and governments. Although the patterns are global, the details differ significantly from country to country. Each dimension of change is complex and all of them interact. Overall, the dynamic nature of wireless communications creates a mixture of confusion and opportunity for stakeholders throughout the world. In contrast to other areas of information technology, wireless communications has yet to converge toward a single technical standard or even a very small number of them. Instead it appears that diversity will endure for the foreseeable future.

This chapter presents an overview of wireless communications and markets in order to enable a deeper understanding of the issues presented above. First, a brief history of wireless communications is presented. Next, the Internet and packet radio are discussed as a predecessor for future high data rate wireless systems. Then, an overview of wireless cellular communications is presented, including discussions of first-generation, second-generation, third-generation wireless voice and data services and transitional technologies. This section provides the context for the discussion on the diffusion for first to second generation systems.

History of Wireless Communications Systems

Throughout most of history, the evolution of communications technologies has been intertwined with military needs and applications. Some of the earliest government-sponsored R&D projects focused on communications technologies that enabled command and control. A synergistic relationship then evolved between the military and commercial sectors that accelerated the technology development process. Now large corporations develop the latest technologies for international industrial and consumer markets shaped by government regulation and international agreements.

Modern wireless communication systems are rooted in telephony and radio technologies dating back to the end of the nineteenth century and the older telegraphy systems dating back to the eighteenth century. Wireless systems are also influenced by and increasingly linked to much newer communications capabilities, such as the Internet, which originated in the 1960s. All wireless systems transmit signals over the air using different frequency transmission bands designated by government regulation. Table 3-1 provides an overview of wireless RF communications systems and services and the frequency bands they use. Each frequency band has both advantages and disadvantages. At low frequencies the signal propagates along the ground; attenuation is low but atmospheric noise levels are high. Because of limited bandwidth available, low frequencies cannot carry enough information for video services. At higher frequencies there is less atmospheric noise but more attenuation, and a clear line of sight is needed between the transmitter and receiver because the signals cannot propagate through objects. These frequencies offer greater bandwidth, or channel capacity.

Frequency Band	Communications Applications	Characteristics
Very low (VLF): 3-30 kHz Low (LF): 30-300 kHz	Long-range navigation, marine radio beacons	Low attenuation, high atmospheric noise
Medium (MF): 300-3000 kHz High (HF): 3-30 MHz	Maritime radio, AM radio, telephone, telegraph, facsimile	Attenuation varies, noise drops at 30 MHz
Very high (VHF): 30-300 MHz Ultrahigh (UHF): 0.3-3 GHz	VHF television, FM two-way radio, UHF television, radar	Cosmic noise, line-of-sight propagation
Super High (SHF): 3-30 GHz	Satellite, radar, microwave	Atmospheric attenuation
30-300 GHz (extremely high, or EHF)	Experimental satellite, radar	Line-of-sight propagation

Table 3-1. Overview of Wireless Radio Frequency Communications Systems and Services²³

This table provides an overview of wireless RF communications systems and services and the frequency bands they use.

In 1895, Guglielmo Marconi demonstrated that electromagnetic radiation could be detected at a distance. Great Britain's Royal Navy was an early and enthusiastic customer of the company that Marconi created to develop radio communications. In 1901 Marconi bridged the Atlantic Ocean by radio, and regular commercial service was initiated in 1907. The importance of this new

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technology became evident with the onset of World War I. Soon after hostilities began, the British cut Germany's overseas telegraphic cables and destroyed its radio stations. Then Germany cut Britain's overland cables to India and those crossing the Baltic to Russia. Britain enlisted Marconi to put together a string of radio stations quickly to reestablish communications with its overseas possessions. The original Marconi radios were soon replaced by more advanced equipment that exploited the vacuum tube's capability to amplify signals and operate at higher frequencies than did older systems. In 1915, the first wireless voice transmission between New York and San Francisco signaled the beginning of the convergence of radio and telephony. The first commercial radio broadcast followed in 1920. The use of higher frequencies (called short waves) exploited the ionosphere as a reflector, greatly increasing the range of communications. By World War II, short-wave radio had developed to the point where small radio sets could be installed in trucks or jeeps or carried by a single soldier. The first portable two-way radio, the Handie-Talkie, appeared in 1940. Two-way mobile communications on a large scale revolutionized warfare, allowing for mobile operations coordinated over large areas.

In the civilian sector, the early development of mobile radio was driven by public safety needs. In 1921, Detroit became the first city to experiment with radio-dispatched police cars. However, transmission from vehicles was limited by the difficulty of producing small, low-power transmitters suitable for use in automobiles. Two-way systems were first deployed in Bayonne, New Jersey, in the 1930s. The system operated in a half-duplex mode; simultaneous transmission and reception, or full-duplex mode, was not possible at the time.

Frequency modulation (FM), invented in 1935, virtually eliminated background static while reducing the need for high transmission power, thus enabling the development of low-power transmitters and receivers for use in vehicles. World War II stimulated commercial FM manufacturing capacity and the rapid development of mobile radio technology. The need for thousands of portable communicators accelerated advances in system packaging and reliability and reduced costs. In 1946 public mobile telephone service was introduced in 25 cities across the United States. The initial systems used a central transmitter to cover a metropolitan area. The inefficient use of spectrum and the coarseness of the electronic filters severely limited capacity: Thirty years after the introduction of mobile telephone service the New York system could support only 543 users.

A solution to this problem emerged in the 1970s when researchers at Bell Laboratories developed the concept of the cellular telephone system, in which a geographical area is divided into adjacent, non-overlapping, hexagonal-shaped "cells." Each cell has its own transmitter and receiver (called a base station) to communicate with the mobile units in that cell; a mobile switching station coordinates the handoff of mobile units crossing cell boundaries. Throughout the geographical area, portions of the radio spectrum are reused, greatly expanding system capacity but also increasing infrastructure complexity and cost.

In the years following the establishment of the mobile telephone service, AT&T submitted numerous proposals to the Federal Communications Commission (FCC) for a dedicated block of spectrum for mobile communications. Other than allowing experimental systems in Chicago and Washington, D.C., the FCC made no allocations for mobile systems until 1983, when the first commercial cellular system—the advanced mobile phone system (AMPS)—was established in Chicago. Cellular technology became highly successful commercially with the miniaturization of subscriber handsets.

The Internet and Packet Radio

As present and future wireless systems have integral data services, it is important to understand the history behind the Internet and digital Packet Radio. The original concepts underlying the Internet were developed in the mid-1960s at what is now the Defense Advanced Research Projects Agency (DARPA), then known as ARPA. The original application was the ARPANET, which was established in 1969 to provide survivable computer communications networks. The ARPANET relied heavily on packet switching concepts developed in the 1960s at the Massachusetts Institute of Technology, the RAND Corporation, and Great Britain's National Physical laboratory. This approach was a departure from the circuit-switching systems used in telephone networks²³.

Telephone systems are based on a connection-oriented or circuit-switched model in which connections are fixed for the duration of a call. Such systems are inefficient when transmission occurs in short bursts separated by long pauses such as is the case with many data services. Packet switching replaces the centralized switches with distributed routers, each with multiple connections to adjacent routers. Messages are divided into "packets" that are independently routed on a hop-by-hop basis. Such an approach allows messages to be multiplexed over the available paths on a statistically determined basis, gracefully adapting the transmissions to traffic level, and optimizing the use of existing link capacity without pre-allocating link bandwidth.

The first ARPANET node was located at the University of California at Los Angeles. Additional nodes were soon established at Stanford Research Institute (now SRI International), the University of California at Santa Barbara, and the University of Utah. The development of a host-to-host protocol, the network control protocol (NCP), followed in 1970, enabling network users to develop applications. At the same time, the ALOHA Project at the University of Hawaii was investigating packet-switched networks over fixed-site radio links. The ALOHANET began operating in 1970, providing the first demonstration of packet radio access in a data network. The contention protocols used in ALOHANET served as the basis for the "carrier-sense multiple access with collision detection" (CSMA/CD) protocols used in the Ethernet local area network (LAN) developed at Xerox Palo Alto Research Center in 1973. The widespread use of Ethernet LANs to connect personal computers (PCs) and workstations allowed broad access to the Internet, a term that emerged in the late 1970s with the design of the Internet protocol (IP). The need to link wired, packet radio, and satellite networks led to the specifications for the transmission control protocol (TCP), which replaced NCP and shifted the responsibility for transmission from the network to the end hosts, thereby enabling the protocol to operate no matter how unreliable the underlying links.

The development of microprocessors, surface acoustic wave filters, and communications protocols for intelligent management of the shared radio channel contributed to the advancement of packet radio technology in the 1970s. In 1972, ARPA launched the Packet Radio Program, aimed at developing techniques for the mobile battlefield, and SATNet, an experimental satellite network. In 1983, ARPA launched a second-generation packet radio program, Survivable Adaptive Networks, to demonstrate how packet radio networks could be scaled up to encompass much larger numbers of nodes and operate in the harsh environment likely to be encountered on the mobile battlefield.

Overview of Wireless Cellular Communications

To understand how Internet-based wireless services will emerge, it is necessary to have an understanding of technological developments that underpin the market as it moves to third generation technology from first and second generation systems.

Existing cellular radio systems are characterized by cells covering geographical areas with their base station (BS) antennas located on top of tall buildings or structures, where they transmit at relatively high power levels to their roving mobile stations²⁵. In current commercial mobile communications systems, the geographical area is divided into clusters of tessellated cells, with the entire frequency allocation assigned to each cluster. By reusing the frequency in each cell, the total number of users increases as more and more cells are deployed. The available bandwidth is partitioned between the cells in each cluster and each mobile user is given a duplex (two-way) channel.

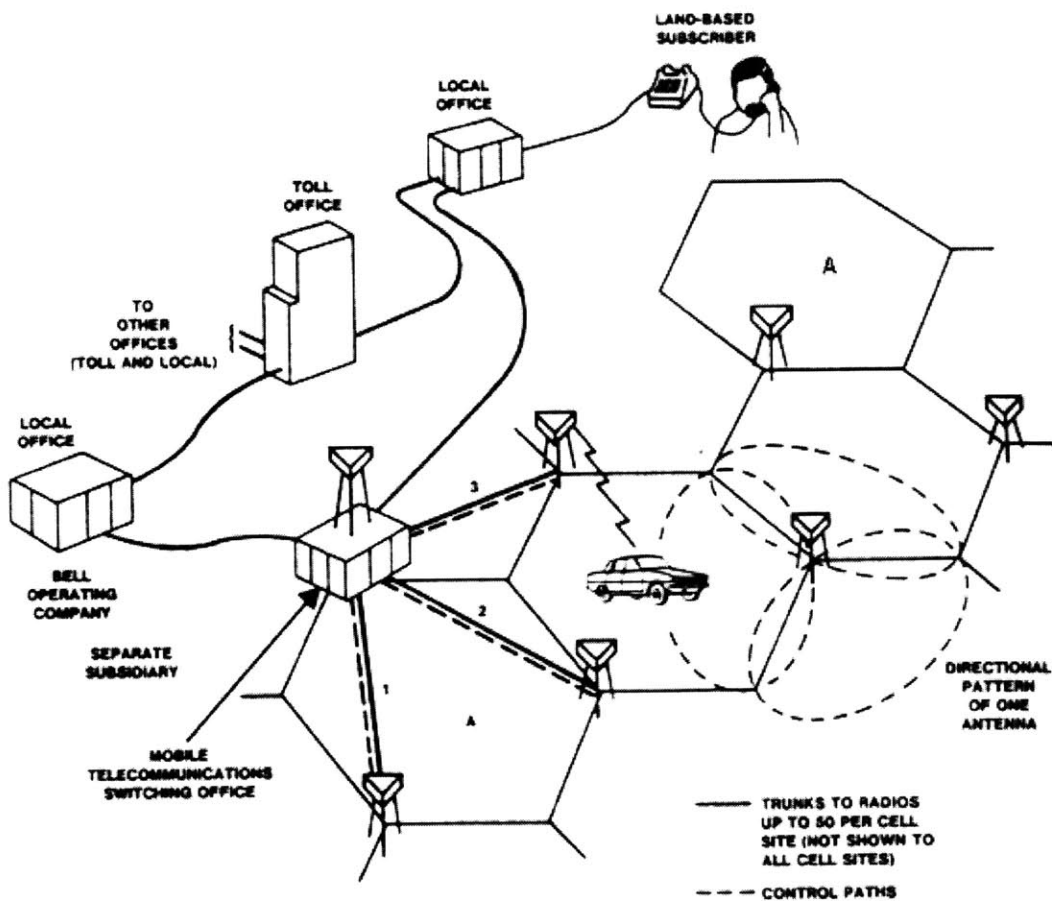


Figure 3-1. Example of a cellular network

In a cellular system, the range of frequencies can be shaped to fit a single cell. Those same frequencies can then be reused in another cell not far away. When a mobile phone begins to leave a cell, the network senses that the signal is becoming weak and connects the call over to the next closest cell so that has a stronger signal, known as handoff.

(source: <http://www.privateline.com/Cellbasics/Cellbasics13.html>)

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Current cells tend to be relatively large, 1 to 20 km wide, with their base stations sited on the top of tall buildings or structures where they command long views. To provide acceptable communications coverage over relatively large areas they transmit at medium to high power levels. A competing technology uses smaller cell size (microcells and picocells) and a corresponding lower transmitter height and transmits at a lower power level.

By lowering the transmitter's power, the range of frequencies can be shaped to fit a single cell. Those same frequencies can then be reused in another cell not far away. This is termed frequency reuse, and demonstrates the frequency efficiency of a cellular system. When a mobile phone begins to leave a cell, the network senses that the signal is becoming weak and connects the call over to the next closest cell so that has a stronger signal. This is known as handoff. A cellular network is illustrated in figure 3-1.

In order to serve metropolitan areas with very high usage rates, it is necessary to shrink the geographic size of each cell to facilitate frequency reuse. In some cases, the cells are shrunk to that of a microcell or picocell within a signal building. This situation has created a demand for cellular base-stations, together with the telephone switching equipment necessary to link cellular systems into the standard telephone communications network. As a result, established manufacturers of telecommunications switching gear have an advantage over market new entrants. Since telephone switches and cellular base stations communicate over proprietary interfaces, service providers face substantial switching costs if they choose to upgrade their cellular networks with advanced (i.e., software defined radio) base-stations manufactured by anyone other than their established switching gear provider.

Current and planned wireless systems use a number of analog and digital techniques to carry voice and data communications. Wireless mobile telephone systems can be divided into three generations, and the protocols for each generation differ on geographic position and service provide network. The first generation (1G), introduced in the 1980s and early 1990s, uses analog cellular and cordless telephone technology. Second-generation (2G) systems transmit speech and low-rate data in digital format. They provide advanced calling features and some non-voice services. There are two categories of second-generation systems. High-tier systems feature high-power transmitters, base stations with coverage ranges on the order of kilometers, and subscribers moving at vehicular speeds. Low-tier systems, serving subscribers moving at pedestrian speeds, have low-power transmitters with a range on the order of 100 meters (m). Some of these systems are designed primarily for indoor use.

Third-generation (3G) systems, planned for main introduction after 2001, are expected to integrate disparate services, including broadband information services that cannot be delivered with second-generation technology. 3G promises to provide many new high data rate and multimedia services. Many users are looking forward to the increased convenience promised by the integration or compatibility of systems. Transition to 3G will be facilitated by an interim planned system called 2.5G. 2.5G systems promise improved data capacity over 2G systems and provides a natural transition from 2G to future 3G capabilities.

Telecommunications standards bodies in other parts of the world (outside of the US) continue to allocate additional blocks of radio spectrum to new 3G wireless services. The U.S. Federal Communications Commission (FCC) plans to allocate new 3G licenses in 2002. European carriers have spent billions of dollars on acquiring spectrum for 3G services. Different regions of the world are allocating different frequency blocks for the 3G licenses, and are also planning on different protocols.

As one can infer from the preceding, there are numerous existing and planned networks, protocols and frequencies used in the global wireless communications industry. Not only will existing (1G) analog and (2G) digital networks remain in place of the foreseeable future, but service providers must also deal with the complications of providing some means for their customers to handoff to competing digital protocols as they roam into the territories of other service providers. For example, VoiceStream Communications has rolled out a global GSM network to allow their customers to roam on their network world wide with one phone. However, these phones cannot take advantage of the larger CDMA and TDMA networks in the US, and thus does not have service in many areas. Another example is AT&T, who provides their customers with two phones with a single US telephone number, one for the US market and one for international markets. A better option for the user would be for providers to allow for mobile phones and devices that could roam on all available networks.

Software defined radios (SDRs), or other technology to allow multiple flexible protocols and air interfaces, could be used to mitigate these interface problems. Additionally, a phone that can be upgraded via software would allow the system operators to migrate more quickly to a new protocol, and provide existing customers with new revenue generating services, as they become available.

Overview of 1G – Analog

Analog cordless telephones have ranges limited to tens of meters and require a dedicated telephone line. Cellular systems have enabled much greater mobility. In establishing cellular service in 1983, the FCC divided the United States into 734 cellular markets (called metropolitan statistical areas and rural service areas), each with an "A-side" and "B-side" cellular service provider. Historically, the designation of A or B indicated the origins of the cellular provider: An A-side provider did not originate in the traditional telephone business and was called a nonwireline carrier, whereas a B-side provider had roots in traditional services and was called a wireline carrier. Each cellular carrier is licensed to use 25 MHz of radio spectrum in the 800-MHz band to provide two-way telephone and data communications for its particular market. Because the U.S. analog cellular system is standardized with Advanced Mobile Phone System (AMPS), any cellular telephone is capable of working in any part of the country.

The AMPS cellular standard uses analog FM and full-duplex radio channels. The frequency division multiple access (FDMA) technique enables multiple users to share the same region of spectrum. This standard supports clear communication and inexpensive mobile telephones, but the transmissions are easy to intercept on a standard radio receiver and therefore are susceptible to eavesdropping.

Outside of the United States and Canada, a wide variety of incompatible analog cellular systems have been deployed. In Europe, several first-generation systems similar to AMPS have been deployed, including: Total Access Communications System (TACS) in the UK, Italy, Spain, Austria and Ireland; Nordic Mobile Telephone (NMT) in many countries; C-450 in Germany and Portugal; Radiocom 2000 in France; and Radio Telephone Mobile System (RTMS) in Italy. These systems use FM (frequency modulation) for speech and FSK (frequency shift keying) for signaling. Handover, as is called handoff in North America, decision is made based on power received at the base stations surrounding the mobile unit. C-450 is an exception, and uses round trip delay measurements. In Japan, a total of 56 MHz is allocated for analog cellular systems. The first analog cellular system, the Nippon Telephone and Telegraph (NNT) system, began operation in the Tokyo metropolitan area in 1979. For other parameters, please refer to Table 3-2.²⁶

The following is an overview of first generation (1G) analog wireless standards^{23,27}:

AMPS

Advanced Mobile Phone System. Developed by Bell Labs in the 1970s and first used commercially in the United States in 1983. It operates in the 800 MHz frequency band. Until recently, it had the largest subscriber base in the world. AMPS was designed with competition in mind, and is thus split into two bands A and B.

The AMPS family of wireless standards was intended to be just another analog radiotelephone standard (e.g. Advanced Mobile Phone Service followed IMTS; Improved Mobile Telephone Service). However, due to the high capacity allowed by the cellular concept, the lower power enabling portable operation and the robust design of AMPS, AMPS has been a stunning success. Until recently, more than half the cellular phones in the world operate according to AMPS standards, which, since 1988, have been maintained and developed by the Telecommunications Industry Association (TIA).

In the United States, a total of 50 MHz in the bands 824-849 MHz and 869-894 MHz is allocated to cellular mobile radio. In a given geographical licensing region, each of two carriers (service providers) controls 25 MHz. The “A” and “B” bands are allocated to “non-wireline” and “wireline” carriers, respectively. AMPS is also used in Canada, Central and South America, and Australia.²⁸ Figure 3-2 is a plot of US AMPS users over time.

N-AMPS is the Narrowband Advanced Mobile Phone System and a derivative of the AMPS system. Developed by Motorola as an interim technology between analog and digital. It has three times greater capacity than AMPS and operates in the 800 MHz frequency range. AMPS is being eventually replaced by newer second-generation (2G) digital cellular systems. U.S. 2G (TDMA and CDMA) systems maintain backward compatibility to AMPS.

C-450

C-450 is a cellular technology found mainly in Germany and Austria operating at 450 MHz. Developed by Siemens, C-450 was opened on a trial basis in September 1985 and fully opened in May 1986. Germany was the first country to adopt the C-450 standard operating in the 451 – 465 MHz frequency range. C-450 was also installed in South Africa during the late 1980's. It was offered as a premium-priced, high quality network, offering nationwide coverage. The system offered a card identity system that distinguished it from other national networks at the time and acquainted the cellular public with what has become an important feature of GSM. Figure 3-3 plots the total C-450 users over time.

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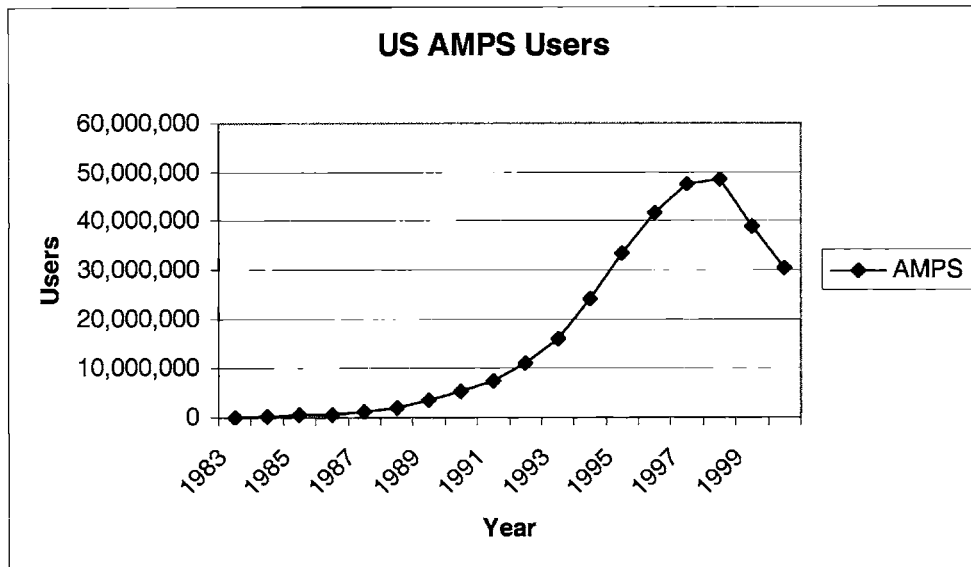


Figure 3-2. US AMPS Subscribers²⁹

This figure demonstrates the number of subscribers for the AMPS system in the United States. Due to its wide regional coverage, it maintained growth until recently. It has started to loose to newer second-generation standards.

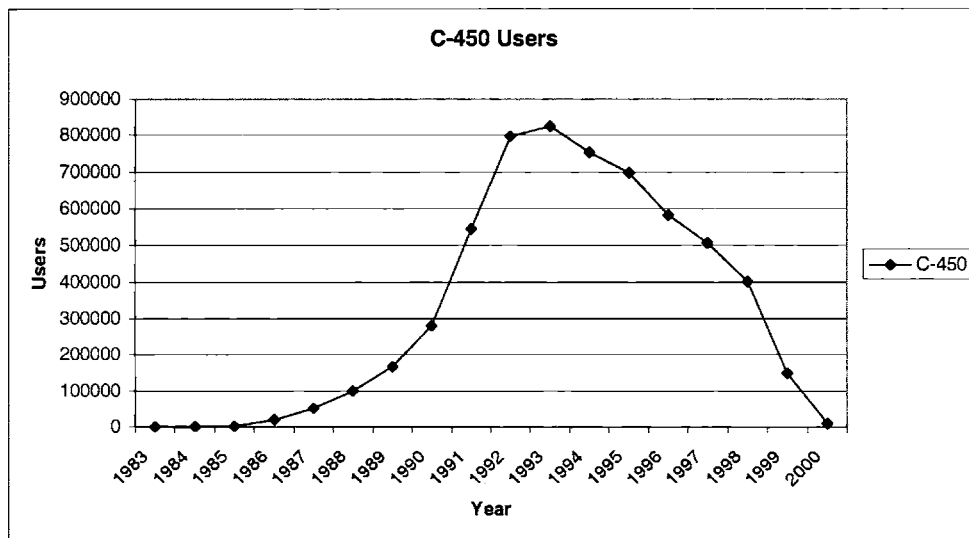


Figure 3-3. Worldwide C-450 Subscribers²⁹

This figure demonstrates the number of subscribers for the C-450 system worldwide. Germany was the first country to adopt the C-450 standard operating in the 451 – 465 MHz frequency range. C-450 was also installed in South Africa during the late 1980's. It was offered as a premium-priced, high quality network, offering nationwide coverage.

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Comvik

Launched in Sweden in August 1981 by the Comvik network. The system met with little success. At its peak it had approximately 19,000 users, and was ultimately decommissioned in 1996. Figure 3-4 is a plot of Comvik subscribers over time.

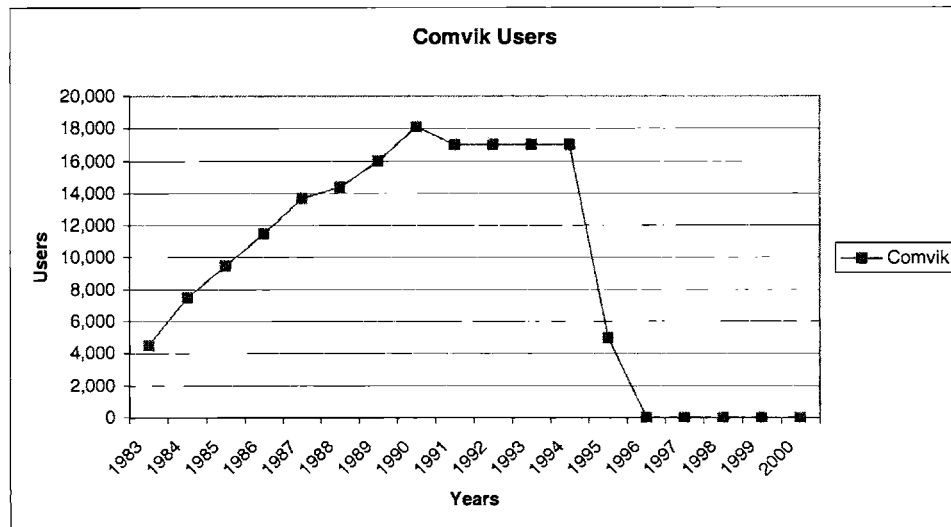


Figure 3-4. Comvik Subscribers²⁹

Launched in Sweden as a regional standard, the Comvik met with little success. It has a maximum of 18,000 subscribers and was eventually decommissioned in the mid-1990s.

NMT-450

Nordic Mobile Telephones/450. Developed specifically by Ericsson and Nokia to service the rugged terrain that characterizes the Nordic countries. Operates in the 450 MHz band. NMT-450 was Europe's first analog cellular service; launched in Denmark, Finland, Norway, and Sweden in 1981. Figure 3-5 plots NMT-450 subscribers over time.

NMT-900

Nordic Mobile Telephones/900. The 900 MHz upgrade to NMT 450 developed by the Nordic countries to accommodate higher capacities and handheld portables. Launched in 1986. NMT-F is the French version. Figure 3-6 plots NMT-900 users over time.

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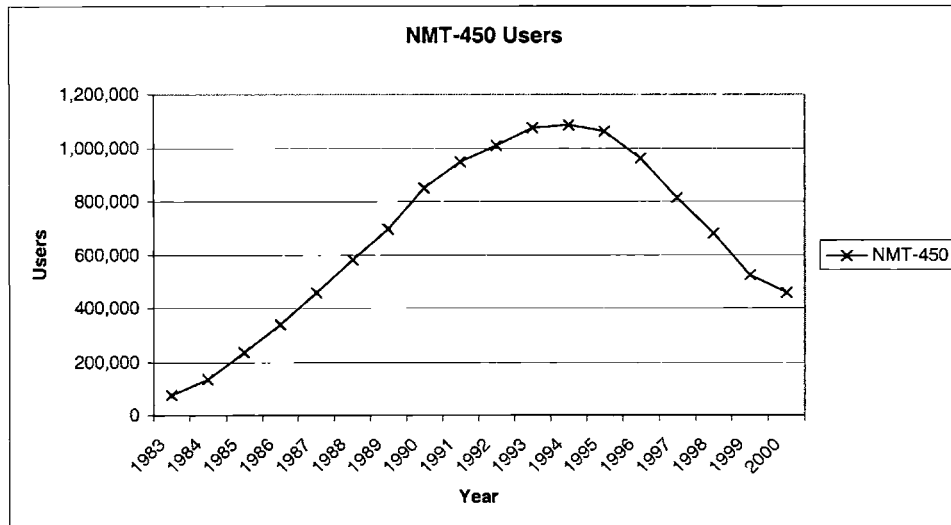


Figure 3-5. NMT-450 Subscribers²⁹

Developed specifically by Ericsson and Nokia to service the rugged terrain that characterizes the Nordic countries, NMT-450 still maintains a niche set of users who value its performance in the terrain of Scandinavia.

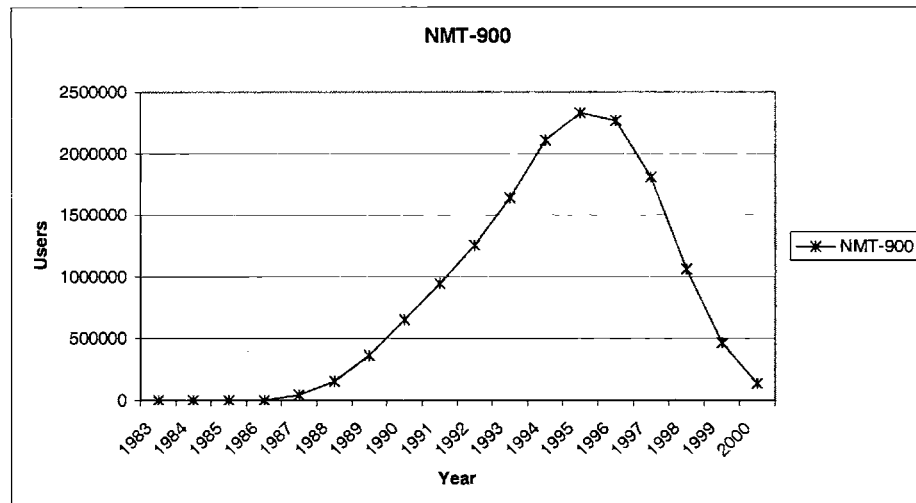


Figure 3-6. NMT-900 Subscribers²⁹

The 900 MHz upgrade to NMT-450 developed by the Nordic countries to accommodate higher capacities and handheld portables.

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NTT

NTT (Nippon Telegraph and Telephone) developed Japan's analog network by operating as a system integrator. A high-capacity version is called HICAP. NTT launched its cellular service in 1979 after installing what came to be known as low capacity (MCS-L1) cellular system operating in the 800 MHz band. Following the government's decision to grant operator licenses to competitors IDO and DDI, NTT decided to change to a new high capacity (MCS-L2) cellular system in 1988, anticipating that subscriber growth would accelerate once IDO and DDI launched their competing services. The high capacity system also operates in the 800 MHz band but has 12.5 kHz rather than 25 kHz channel interleaving.

Initially when NTT established its cellular service and for the next decade, most subscribers wanted car mounted terminals (CMTs). CMTs accounted for approximately 90% of the market until IDO and DDI launched their competing services. In 1988, the high capacity system was introduced in the same band. The number of channels was further increased by frequency interleaving, resulting in an overall fourfold increase in the number of channels to 2400. Simultaneously, hand-portables were chosen by a fast growing share of NTT's new subscribers with the result that by the early 1990 call patterns and cellular phone usage had changed remarkably from that which NTT originally planned for. Figure 3-7 is a plot of NTT subscribers over time.

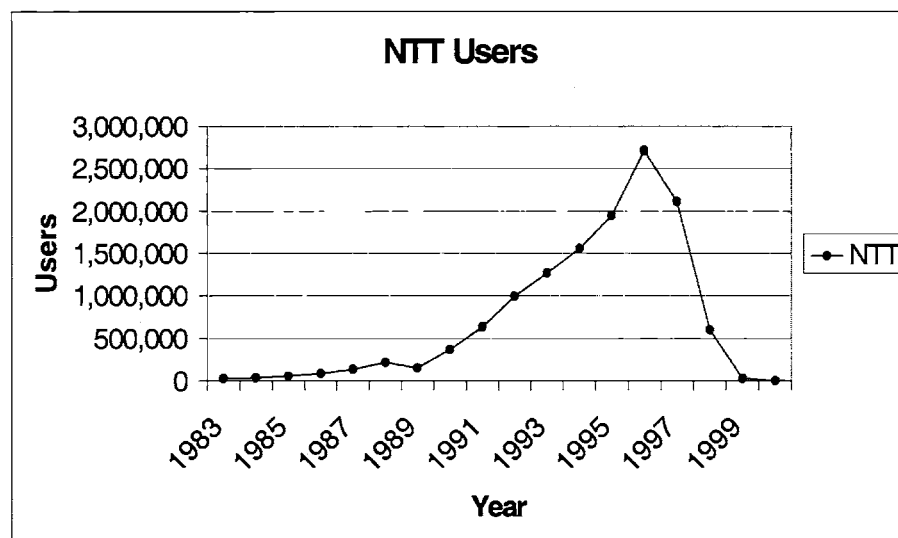


Figure 3-7. NTT Subscribers²⁹

Originally launched in 1979, NTT's original analog system operated in the 800 MHz band. This system has been replaced by newer second-generation technology.

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RC-2000

Radiocom 2000. French system launched November 1985. Figure 3-8 is a plot of the RC-2000 subscribers over time. It met with limited success in light of competition with emerging 2G systems.

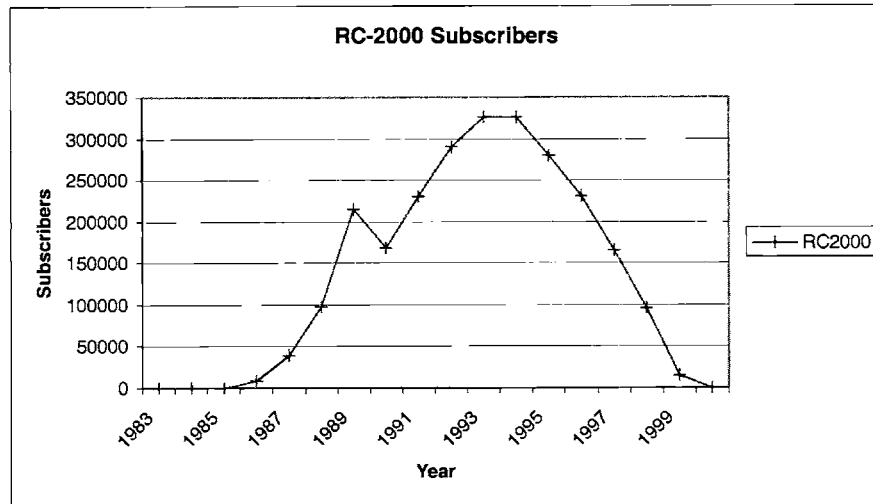


Figure 3-8. RC-2000 Subscribers²⁹

French system launched November 1985. It met with limited success due to its limited regional coverage, and subsequent competition with second-generation standards.

TACS

Total Access Communications System, similar to AMPS, but operating in the European 900 MHz analog cellular frequency range. First used in the United Kingdom in 1985. Also used in Japan, where it is called J-TACS. The UK Department of Trade and Industry (DTI) specified TACS in 1983 as the technology of choice for analog operators in the UK. It is a derivative of AMPS, but uses slightly narrower channel spacing and is located in the 900 MHz band. Like AMPS, it was specified with competition in mind and is thus split into two bands, A and B. Due to unforeseen growth and capacity pressure in the South East of England, by 1986 both operators demanded that additional frequencies be allocated. The E-TACS (extended TACS) came into widespread use in the UK during early 1989. The ETACS specification, which included authentication, was issued by the DTI in 1989. International uptake was good by the standards of most nationally specified analog technologies. TACS was implemented in Ireland, Austria, Spain, Italy and Malta in Europe and a total of 25 countries worldwide.

The TACS European cellular systems were eventually superseded by GSM systems, a newer (2G) digital cellular system.

In 1987, cellular radio was deregulated in Japan and two new operators were introduced. One of the new competitors, IDO, began operation of the NTT high capacity system in December 1988, covering the Kanto-Tokaido areas in the bands 860-863.5/915-918.5 MHz. The third cellular carrier is the DDI Cellular Group, which provides coverage outside the metropolitan areas using the JTACS/NTACS systems (based on the European TACS system) in the bands 860-870/915-925 MHz and 843-846/898- 901 MHz. Following DDI, IDO also introduced NTACS in the bands

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843-846/898-901 MHz and 863.5-867/918.5-922 MHz. IDO and DDI formed a partnership to provide nationwide service by introducing roaming capabilities between the two systems.

Figure 3-9 is a plot of worldwide TACS subscribers over time.

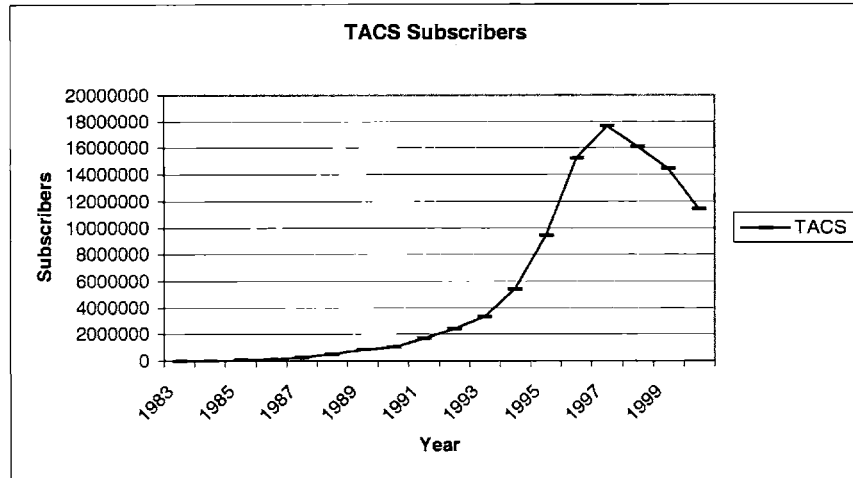


Figure 3-9. TACS Subscribers²⁹

The most successful European first generation system, the TACS European cellular systems were eventually superceded by GSM systems, a newer (2G) digital cellular system. It was a derivative of the North American AMPS standard, operating at a different radio frequency interface.

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Standard	Mobile TX/ Base TX (MHz)	Channel Spacing (KHz)	Number of Channels	Region
AMPS	824-849/ 869-894	30	832	The Americas ¹
TACS	890-915/ 935-960 ⁱⁱ	25	1000	Europe ¹
NMT-450	453-457.5/ 463-467.5	25	180	Europe ¹
NMT-900	890-915/ 935-960	12.5	1999	Europe ¹
RTMS	450-455/ 460-465	25	200	Italy
NTT	925-940/870-885 ^{iv}	25/6.25 ⁱⁱⁱ	600/2400	Japan
	915-918.5/860-863.5 ^v	6.25 ⁱⁱⁱ	560	
	922-925/867-870 ^v	6.25 ⁱⁱⁱ	480	
C-450	450-455.74/ 460-465.74	10 ⁱⁱⁱ	573	Germany
				Portugal

- i. AMPS is also used in Australia. AMPS, TACS, and NMT are all used in parts of Africa and Southeast Asia.
- ii. The bands 890-915/935-960 MHz were subsequently allocated to GSM in Europe.
- iii. Frequency interleaving using overlapping or “interstitial” channels: the channel spacing is half the nominal channel bandwidth.
- iv. NTT DoCoMo, nationwide.
- v. IDO, in the Kanto-Tokaido areas.
- vi. DDI, outside the Kanto-Tokaido areas.

Table 3-2. Examples of Analog Cellular System Parameters^{26,28}

This table summarizes the technical parameters of each first-generation cellular standard.

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Overview of Second-Generation (2G) Technology

Spurred by growing consumer demand for wireless services, standards organizations in North America, Europe, and Japan specified technologies to meet consumer expectations and make more efficient use of allocated spectrum bands. These second-generation systems use advanced digital signal processing, compression, coding, and network-control techniques to conserve radio bandwidth, prevent eavesdropping and unauthorized use of networks, and also support additional services (e.g., voice mail, three-way calling, and text transmission retrieval). These 2G mobile communications are based on Personal Communications Service (PCS), a set of digital cellular technologies that work over CDMA (IS-95A), GSM and TDMA (S-136) air interfaces. The data transfer rate ranges from 7 Kbps to 14.4 Kbps.

In the United States, second-generation technologies have been deployed in the original 800-MHz cellular bands and in personal communications bands around 1900 MHz that were allocated by the FCC between 1995 and 1997. In Europe and most other parts of the world, second-generation technologies are deployed in the 900-MHz cellular bands and in 1800-MHz personal communications bands. Japan operates digital cellular systems in various bands between 800 MHz and 1500 MHz as well as a personal communications band near 1900 MHz.

The most widespread second-generation techniques include three high-tier standards²³: the European standard, GSM; and two North American standards, IS-136, a time division multiple access (TDMA) technique, and IS-95, a code division multiple access (CDMA) technique. The GSM standard, which has been adopted in more than 100 countries, specifies a complete wide-area communications system. The other two standards specify only the communications between mobile telephones and base stations. A separate standard, IS-41, governs communications between mobile switching centers and other infrastructure elements in the United States. Table 3-3 is a summary of the high-tier 2G systems.

Among low-tier standards, the personal handyphone system (PHS) provides mobile telephone services to several million Japanese subscribers. Two other standards, digital European cordless telecommunications (DECT) and cordless telephone second generation (CT2), from the basis of several wireless business telephone (i.e., private branch exchange, or PBX) products. A fourth low-tier system is the personal access communications system (PACS), a U.S. standard. Although PACS had attracted considerable industry interest, it was not widely deployed. Table 3-4 is a summary of the low-tier wireless systems.

The development of low-rate digital speech coding techniques and the continuous increase in the device density of integrated circuits (i.e., transistors per unit area) have made digital baseband second-generation systems viable. Signal digitization allowed the use of time division multiple access (TDMA) and code division multiple access (CDMA) as alternatives to frequency division multiple access (FDMA). With TDMA, the usage of each radio channel is partitioned into multiple timeslots, and each user is assigned a specific frequency/timeslot combination. Thus, only a single mobile in a given cell is using a given frequency/timeslot combination at any particular time. With CDMA (which uses direct sequence spreading), multiple mobiles in a given cell use a frequency channel simultaneously, and the signals are distinguished by spreading them with different codes. An obvious advantage of both TDMA and CDMA is the sharing of radio hardware in the base station among multiple users.

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System	IS-95 (CDMA)	GSM ⁱ	IS-54/IS-136 (TDMA)	PDC ⁱⁱ
Region	Worldwide	Worldwide	Americas	Japan
Access method	CDMA ⁱⁱⁱ	FDMA ^{iv} /TDM A ^v	FDMA ^{iv} /TDM A ^v	TDMA ^v
Frequency bands (megahertz)	824-849, 869-894, 1850-1910, 1930-1990	890-915, 935-960 1710-1785, 1805-1885 1850-1910, 1930-1990	824-849, 869-894	810-826, 940-956, 1477-1489, 1429-1441, 1501-1513, 1453-1465
Carrier spacing (kilohertz)	1250	200	30	25
Channels per carrier	Soft capacity (limited by noise and interference)	8	3	3

- i. Global system for mobile communications.
- ii. Pacific digital cellular.
- iii. Code division multiple access.
- iv. Frequency division multiple access.
- v. Time division multiple access.

Table 3-3. Summary of the Properties of the Principal High-Tier 2G Systems²⁸

CDMA, GSM, TDMA, and PDC are the widely deployed worldwide second-generation cellular standards. This table summarizes their technical standards.

The use of TDMA or CDMA digital architectures also offers additional advantages, including:

- A more natural integration with the evolving digital wireline network.
- Flexibility for mixed voice/data communication and the support of new services.
- A potential for further capacity increases as reduced rate speech coders are developed.
- Reduced RF transmit power (increasing battery life in handsets).
- Data encryption for communication privacy.
- Reduced system complexity (mobile-assisted handoffs, fewer radio transceivers).

The following describes the high-tier standards in greater detail:

IS-95 - Code Division Multiple Access (CDMA - now referred to as cdmaOne)

Developed originally by Qualcomm, CDMA is characterized by high capacity and small cell radius, employing spread-spectrum technology and a special coding scheme. CDMA was adopted by the Telecommunications Industry Association (TIA) in 1993 as EIA/TIA IS-95 standard, and is implemented in North America. IS-95 allows many users to share a common channel for transmission. In IS-95, "soft-handoffs" is supported, whereby a mobile unit making the transition between cells maintains links with both base stations during the transition. The mobile's receiver combines the signals from the two base stations in the same manner as it would combine signals

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associated with different multipath components. The IS-95 CDMA approach offers a number of benefits, including increased capacity, elimination of the need for planning frequency assignments to cells, and flexibility for accommodating different transmission rates. Like IS-54 (TDMA), IS-95 is also a dual-mode standard designed for the existing North America cellular bands: IS-95 terminals can operate either in the CDMA mode or the AMPS mode.

System	CT2/CT2+ ⁱ	DECT ⁱⁱ	PHS ⁱⁱⁱ	PACS ^{iv}
Region	Europe, Canada	Europe	Japan	United States
Access method	FDMA	FDMA/TDMA	FDMA/TDMA	FDMA/TDMA
Frequency band (megahertz)	864-868, 944-948	1880-1900	1895-1918	1850-1910, 1930-1990
Carrier spacing (kilohertz)	100	1728	300	300
Number of carriers	40	10	77	16 per pair
Channels per carrier	1	12	4	8 per pair

- i. Cordless telephone second generation.
- ii. Digital European cordless telecommunications.
- iii. Personal handyphone system.
- iv. Personal access communications system.

Table 3-4. Low-Tier Wireless/Personal Communications Systems²⁸

This table summarizes the low-tier wireless technical standards. The personal handyphone system (PHS) provides mobile telephone services to several million Japanese subscribers. Two other standards, digital European cordless telecommunications (DECT) and cordless telephone second generation (CT2), from the basis of several wireless business telephone (i.e., private branch exchange, or PBX) products. A fourth low-tier system is the personal access communications system (PACS), a U.S. standard. Although PACS had attracted considerable industry interest, it was not widely deployed.

There are now a number of variations of CDMA, in addition to the original Qualcomm-invented N-CDMA (originally just 'CDMA', also known in the US as IS-95). Latest variations are B-CDMA, W-CDMA and composite CDMA/TDMA. B-CDMA is the basis for 3G UMTS (3G is covered later in this overview section).

Traditional uses of spread spectrum are in military operations. Because of the wide bandwidth of a spread spectrum signal, it is very difficult to jam, difficult to interfere with, and difficult to identify. This is in contrast to technologies using a narrower bandwidth of frequencies. Since a wideband spread spectrum signal is very hard to detect, it appears as nothing more than a slight rise in the "noise floor" or interference level. With other technologies, the power of the signal is concentrated in a narrower band, which makes it easier to detect.

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Increased privacy is inherent in CDMA technology. CDMA phone calls are secure from the casual eavesdropper since, unlike an analog conversation, a simple radio receiver cannot pick individual digital conversations out of the overall RF radiation in a frequency band.

Global System for Mobile Communications (GSM)

The large number of different analog systems used in Europe did not represent an ideal situation from a subscriber point of view, i.e., subscribers could not roam on the various incompatible European 1G standards. This, together with the need to accommodate an increasing number of users and to establish compatibility with the evolution of the fixed network towards digital systems, led the Conférence Européenne des Postes et Télécommunications (CEPT) to establish a "Groupe Spécial Mobile" in 1982. The work of that group became the GSM system.

The GSM system was primarily expected to provide better quality, pan-European roaming, and the transmission of data for fax, e-mail, files, etc. The design also offered the opportunity to specify a system for lower-cost implementations and the potential for increased spectral efficiency. Finally, a high degree of flexibility and openness to future improvements were recognized as important and taken into account.

GSM is the most popular worldwide digital cellular communication standard with over 100 GSM networks now operational. Originally, GSM was intended to be operated only in Bands around 900 MHz. In early 1989, the UK Department of Trade and Industry started an initiative that led to the assignment of 150 MHz of bandwidth near 1.8 GHz for Personal Communications Network (PCN) in Europe, and to the choice of GSM as a standard for that application. This system is called DCS-1800, for Digital Cellular System 1800. Its definition meant translating the specifications to the new band and modifying some parts for accommodating overlays of micro and macro cells. Cellular and PCN are certainly the most prominent applications, but GSM is currently also extended to include "group calls" and "push to talk" for private mobile radio (PMR) applications. In the cellular area, GSM has experienced tremendous growth since the start of deployment in 1993.

As of September 2001, there were over 305 million subscribers in Western Europe and over 595 million subscribers throughout the world²⁹. As described above, the Personal Communications Service (PCS) also uses the GSM protocol. The PCS frequency band is 1850 to 1990 MHz, a band that encompasses a wide range of digital cellular standards like N-CDMA and GSM 1900. Single-band GSM 900 phones cannot be used on PCS networks. PCS networks operate throughout North America.

Time Division Multiple Access (TDMA): IS-54/IS-136 in North America

To meet the growing need to increase cellular capacity in high-density areas, the Electronic Industries Association (EIA) and the Telecommunications Industry Association (TIA) adopted the IS-54 standard based on TDMA. IS-54 retains the 30-kHz channel spacing of AMPS, which was discussed before, to facilitate evolution from analog to digital systems. Since systems using the IS-54 standard must operate in the same spectrum used by the existing AMPS systems, the IS-54 standard is "dual mode", which means that it provides for both analog (AMPS) and digital operation. This is necessary to accommodate "roaming" subscribers, given the large embedded base of AMPS equipment.

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TDMA digital systems get their name by dividing a single channel into a number of timeslots, with each user getting one out of every few slots. This requires digitizing voice, compressing it and transmitting it in regular bursts. TDMA triples the capacity of cellular frequencies (as compared to AMPS) by dividing a 30 kHz cellular channel into 3 timeslots, which supports 3 users in strict alternation.

Personal Digital Cellular (PDC) in Japan

In Japan, there were two different types of analog cellular systems (NTT and JTACS) that developed from different backgrounds. From the perspective of the user, a single air interface was desirable for providing roaming capability among different mobile networks. A development study for digital cellular systems with a common air interface was initiated in 1989 under the auspices of the Ministry of Posts and Telecommunications (MPT). The new digital system was established in 1991 and named Personal Digital Cellular (PDC). The PDC system is based on TDMA, with three slots multiplexed onto each carrier, similar to IS-54. The channel spacing is 25 kHz with interleaving to facilitate migration from analog to digital. A total of 80 MHz is allocated to PDC; the frequency bands are 810-826 MHz paired with 940-956 MHz and 1429-1453 MHz paired with 1477-1501 MHz.

A similar system is the Personal Handy System (PHS). PHS is a TDMA Japanese-centric system that offers high-speed data services and superb voice clarity. Really, it is a wireless local loop system with only 300 m to 3 km coverage. Wireless Local Loop systems are usually found in remote areas where fixed-line usage is impossible. Most modern WLL systems use CDMA technology, with the PHS system an exception.

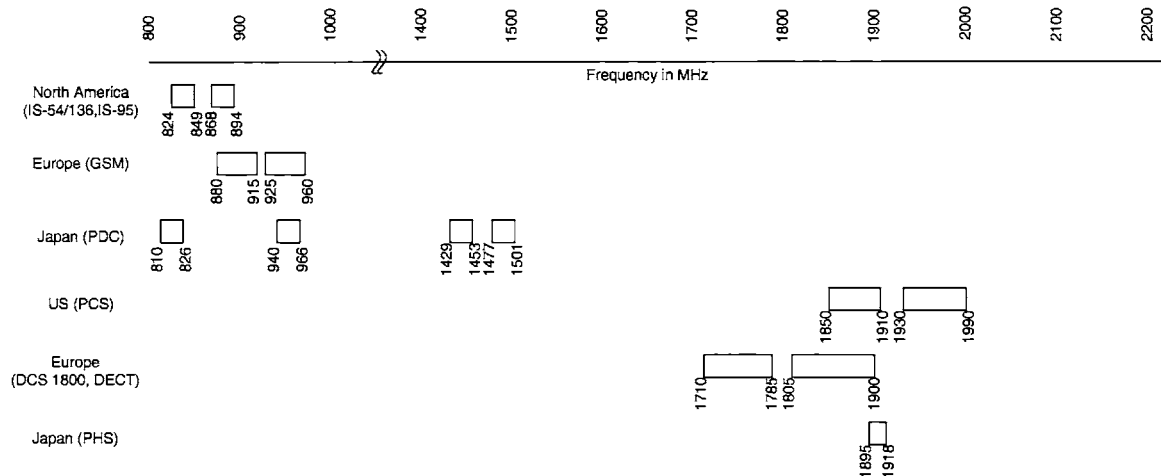


Figure 3-10. Worldwide Spectrum Allocation for Major Cellular Systems

This figure provides an overview of the worldwide radio frequency spectrum allocation for all major first- and second-generation cellular systems.

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2G Mobile Data Services²³

To understand the demand for 2.5G and 3G wireless data services, it's important to understand the history and current mobile data infrastructure.

Commercial packet-switched mobile data services emerged after the success of short-message, alphanumeric one-way paging systems. Mobile data networks provide two-way, low-speed, packet-switched data communication links with some restrictions on the size of the message (10 to 20 kilobytes) in early systems. Services provided by mobile data networks include the following:

- Transaction processing (credit card verification, paging, notice of voice or electronic mail);
- Broadcast services (general information, weather and traffic advisories, advertising);
- Interactive services (terminal access to host, remote LAN access, games); and
- Multicast service (subscription information services, law enforcement, private bulletin boards).

The first commercial mobile data network was Ardis, a private network developed in 1983 by IBM Corporation and Motorola to enable IBM to provide computing facilities in the field. By 1990, Ardis was deployed in more than 400 areas and 10,700 cities and towns using 1,300 base stations. By 1994 Ardis (then owned by Motorola) provided nationwide roaming for approximately 35,000 users, at a rate of 45 million messages per month, and a data rate of 19.2 kbps.

In 1986, Swedish Telecomm and Ericsson Radio Systems AB introduced Mobitex and deployed it in Sweden. This system is available in the United States, Norway, Finland, Great Britain, the Netherlands, and France. The system supports a data rate of 8 Mbps and nationwide roaming. This service is distributed by RAM Mobile Data in the United States, where by 1994 it had 12,000 subscribers. A total of 840 base stations are connected to 40 switching centers to cover 100 metropolitan areas and 6,300 cities and towns.

Cellular digital packet data (CDPD) technology was developed by IBM, which together with nine operating companies formed the CDPD Forum to develop an open standard and multivendor environment for a packet-switched network using the physical infrastructure and frequency bands of the AMPS systems. The CDPD specification was completed in 1993 with key contributions from IBM, McCaw Cellular Communications, Inc., and Pacific Communications Sciences, Inc. Deployment of the 19.2-kbps CDPD infrastructure, designed to make use of idle channels in analog cellular systems, commenced in 1995.

In the 1990s Metricom, Inc., developed a metropolitan-area network that was deployed first in the San Francisco Bay area and then in Washington, D.C. The signaling rate of this system is advertised at 100 kbps but the actual data rate is substantially slower. The Metricom system uses "frequency hopping" spread-spectrum (FHSS) technology in the lower frequencies (around 900 MHz) of the unlicensed industrial, scientific, and medical (ISM) bands.

In 1996 the European Telecommunications Standards Institute (ETSI) standard for mobile data services, trans-European trunked radio (TETRA), was completed. It is currently being used primarily for public safety purposes.

Work was also performed to enhance the digital cellular and personal communications technologies. More recently, the (2G) digital cellular standards (GSM, IS-95, PHS, PACS, and IS-136) were updated to support packet-switched mobile data services at a variety of data rates. Although many services are available over these networks, the mobile data market has grown much more slowly than have voice services.

2.5G Systems: Transition from 2G to 3G systems

The general data transmission speed of 2G networks is sufficient for unidirectional services such as simple message service (SMS), but too slow for transmitting the large amounts of data required for video and other bandwidth intensive applications. The resources wasted by excessive channel occupancy are also a serious problem as demand for mobile services has increased. Data upgrades to existing 2G systems are termed 2.5G and provide modern mobile data communications capability.

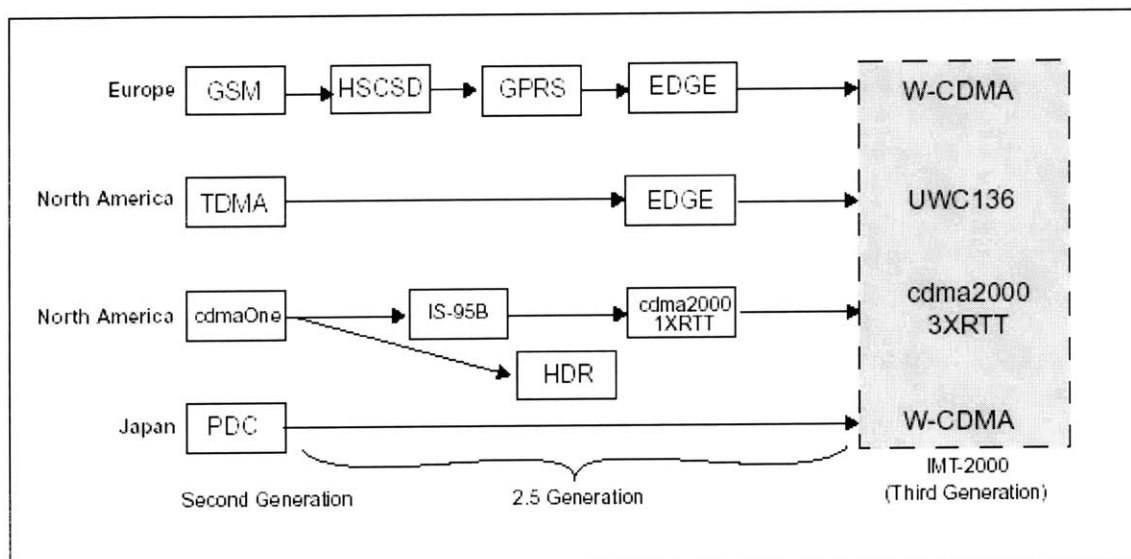
2.5G is being used as a label to describe a step on the way to full 3G requirements. There is no fixed standard for 2.5G, but it is part of an evolutionary process permitting increased data rate by modification of the existing 2G systems (see Figure 3-13). Modifications will allow sufficient bandwidth to make applications such as Internet access viable in advance of full 3G compliance. More importantly, it will also allow operators to test the market and consumer appetite for these types of services. A prime example is the addition of GPRS to current GSM networks. The use of GPRS and high-speed circuit-switched data HSCSD in GSM networks will enable many 3G-type applications. The equivalent in code-division multiple access (CDMA) networks is High Data Rate (HDR) and 1XRTT.

Third-generation (3G) mobile communication systems as proposed for IMT-2000 or Universal Mobile Telecommunications System (UMTS) in Europe were originally conceived as *replacement* systems that would provide much higher data rates than are available from an unmodified second-generation (2G) digital (voice) network and also provide a high-quality voice switched network. The air interfaces for 3G systems are designed to use the frequency spectrum more efficiently than those employed in current 2G systems. The originators of 3G technology did not anticipate that current 2G systems would be amenable to enhancements such as General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE). These modifications can boost data rates to approximately half those that can be realized in a practical 3G network. The GPRS adaptation changes the existing 2G network into one that can handle both voice (with circuit switching) and data (by the introduction of packet switching). Packet-switched connections are recognized as a more efficient way of handling data traffic. The EDGE adaptation builds on GPRS by changing the air interface to make it more spectrally efficient.

In comparison with older circuit switched data transmission architectures, in 2.5G, information to be transmitted is divided into “packets.” It is then reassembled at the receiving end. This means that, rather than dedicating a radio channel to a mobile data user for a fixed period of time, the available radio resource can be concurrently shared among several users. In this way, the radio resources are used only when users are actually sending or receiving data. As a result, operators can provide faster transmission speeds with flexible tariff plans and maximize network resources.

The options available to operators wishing to roll out a wireless voice and data network are summarized in Figure 3-11³⁰. The alternative that any given operator will choose depends on a complex of issues including the upgrade potential of the current infrastructure. GSM, TDMA, and CDMA 2G (cdmaOne) network operators have different migration paths, due to the inherent architecture of their existing networks.

Driving the demand to upgrade to next generation data (NGD) technologies is both the need for higher efficiency spectrum utilization, and the demand for mobile data services. The Yankee Group believes there will be over 70 million NGD users in Europe by 2005.³¹ This is expected to be a mixture of 2.5G and 3G services. GPRS, HSCSD, and EDGE (commonly referred to as 2.5G) will constitute a large percentage of total NGD users by 2005. Yankee Group also believes that every GSM operator in Europe will deploy GPRS, and by 2005, GPRS users will almost match the number of voice-only users. By comparison, HSCSD and EDGE deployments will be limited. By mid-2001, there were 13 European HSCSD contracts deployed or awarded and it is unlikely that further would be contracted. Yankee expects there to be between eight and ten EDGE deployments in Europe by 2005.



EDGE = Enhanced Data Rates for GSM Evolution
GPRS = General Packet Radio Service
GSM = Global System for Mobile Communications
HDR = High Data Rate
HSCSD = High-Speed Circuit-Switched Data
PDC = personal digital cellular
TDMA = time-division multiple access
W-CDMA = wideband code-division multiple access
Source: Dataquest (September 2000)

Figure 3-11. Evolution from 2G to 3G Networks

This figure describes the likely migration paths from second-generation to third generation networks, with likely 2.5G “interim” data standards also shown. For example, the North American cdmaOne standard migration is to IS-95B to cdma2000 1XRTT to ultimately cdma2000 3XRTT. There is also an intermediate HDR system for cdmaOne, bypassing IS-95B, with no upgrade path to 3G functionality. Each data standard is further discussed in the thesis text.

(Source: Gartner Dataquest (September 2000))

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High-Speed Circuit-Switched Data (HSCSD)

HSCSD is circuit-switched wireless data transmission for mobile users at data rates up to a maximum of 57.6 Kbps, four times faster than the standard data rates of the Global System for Mobile (GSM) communication standard. HSCSD is comparable to the speed of many computer modems that communicate with today's fixed telephone networks. HSCSD is an evolutionary technology on the way to Universal Mobile Telecommunications Service (UMTS)³².

There are currently 13 operators that have either deployed or are planning to deploy HSCSD in Western Europe, and an estimated 32 worldwide. Nokia claims to have supplied over 20 of these with its HSCSD solution. Even though vendors will probably offer HSCSD upgrades for nominal fees to encourage take up, the Yankee Group believes it unlikely that any additional systems will be deployed across Europe. The majority of operators deploying HSCSD run capacity-rich networks (either GSM-1800 or dual-band networks). HSCSD has been dubbed by some as the red herring migration technology for providing next-generation data. It can deliver maximum speeds of 57.6 Kbps and is a low-cost technology to implement. However, it is a circuit-switched technology and is capacity inefficient.

At present, HSCSD data rates are no faster than 28.8 Kbps have been implemented, which is fast enough to run basic applications and double the speed GSM can reach. HSCSD threatens to be squeezed out of the market by its late arrival and GPRS's reduced time-to-market. The majority of vendors have either removed it from their NGD portfolio or have scaled back their efforts in promoting it.

Although HSCSD has not succeeded in the NGD market, it is still superior to GPRS for less bursty applications and is likely to evolve into a niche commodity. HSCSD will be able to provide video conferencing approximately three years before packet-based technologies can offer a suitable alternative, although users will probably pay a premium for the service. The majority of traffic generated from NGD is expected to be bursty and relatively time-insensitive. GPRS is better suited to delivering this type of data. In the majority of cases HSCSD will be deployed alongside GPRS.

General Packet Radio Service (GPRS)³³

GPRS is a data services upgrade to any GSM network. It allows GSM networks to be truly compatible with the Internet by using a packet-mode technique to transfer bursty traffic in an efficient manner. It allows transmission bit rates from 9.6 Kbps to more than 50 Kbps per user. The two key benefits of GPRS are a better use of radio and network resources and completely transparent Internet Protocol (IP) support. GPRS optimizes the use of network and radio resources. It uses radio resources only when there is data to be sent or received. As a true packet technology it allows end user applications to only occupy the network when a payload is being transferred, and so is well adapted to the very bursty nature of data applications. Another important feature of GPRS is that it provides immediate connectivity and high throughput.

GPRS is by far the favored HSD technology among European operators. Unlike HSCSD, it sends data in packets. Although it can achieve data rates of up to 115 Kbps, initial service will only achieve data rates of 30–50 Kbps. The cost, speed of deployment, and implementation of GPRS are greater than that of HSCSD. However, GPRS enables operators to familiarize themselves with operating a packet network, test out applications (which could be adapted for 3G), and create demand for high-speed mobile data services. Perhaps the biggest benefit of GPRS over HSCSD

is that GPRS is an always-on technology ready to receive data without taking up a whole channel and reducing capacity in the network. For operators GPRS is very capacity-efficient, and for users GPRS is likely to be relatively cheap. Alternative pricing structures by packets or bandwidth are more appropriate than traditional time-based charging.

UK operator BT Cellnet launched the first commercial GPRS service in Europe at the end of June 2000, using a Motorola network. By the middle of 2001, there were eight to ten European operators offering a somewhat limited GPRS service. The Yankee Group estimates that over 50 GPRS contracts have already been awarded in Europe,³¹ and there are a number of trials and roll-outs occurring across Europe including German operator T-Mobil, Finnish operator Sonera (fourth quarter), French operator France Telecom Mobiles (fourth quarter), and UK operators Vodafone and Orange.

In the U.S., where there always seems to lag Europe in wireless system roll-out, several companies have deployed GPRS service. AT&T was the first to offer GPRS service in Seattle, Washington with support for a variety of devices - additional phones, PDAs (personal digital assistants) and wireless modems. AT&T Wireless said its network - which is based on the GSM (global system for mobile communications) and GPRS (general packet radio service) standards -- provides unified messaging for customers' voice mail and e-mail and lets users flip between voice and data transmissions while using their phone. For example, a user can receive an e-mail while on a voice call. Basic features, such as mobile Internet and e-mail access, two-way text messaging, voice mail, and multiparty calling, also are included.⁴¹ AT&T has also announced the availability of GPRS service in Las Vegas, Phoenix and Portland (OR), and announced that they have spectrum to roll-out GPRS and 3G in 80 of 100 major US markets.³⁴

Other announced GPRS rollouts in the US include Cingular Wireless in Seattle. The new GPRS service, which introduces packet data transmission technology into its existing GSM network, is an extension of Cingular's expertise leveraging its extensive and seamless nationwide Mobitex network. Additionally, with the Motorola Timeport 7389i tri-band phone, consumers can roam anywhere on GSM across the U.S. and Canada and with Cingular's GSM partners overseas. Cingular Wireless Internet Express is expected to be available in all of Cingular's GSM markets by early 2002.³⁵

However, to date the roll-out of GPRS has been hampered to date by a lack of terminals supporting the new data standard. A leading Delhi, India operator is evaluating the situation right now. Its spokesperson said, "The GPRS experience has not been very good worldwide. We are currently re-examining whether we should implement GPRS, which is a 2.5G mobile technology, or whether we should move directly to Enhanced Data GSM rate (EDGE), which is 2.75G."³⁶

Enhanced Data rate for GSM Evolution EDGE

UWC-136, the next generation of data heading towards third generation and personal multimedia environments builds on GPRS and is known as Enhanced Data rate for GSM Evolution (EDGE). It will allow GSM operators to use existing GSM radio bands to offer wireless multimedia IP-based services and applications at theoretical maximum speeds of 384 kbps with a bit-rate of 48 kbps per timeslot and up to 69.2 kbps per timeslot in good radio conditions.

There is much speculation over whether operators will bypass EDGE altogether in favor of moving directly from GPRS to UMTS (a 3G standard). Theoretically, EDGE enables data rates of

384 Kbps, and up to 511 Kbps, if inside. However, in reality, EDGE will provide speeds of approximately 80–100 Kbps. This is still double the speed of GPRS, but it is not fast enough to deliver major benefits over GPRS. Additionally, vendor estimates indicate that the cost of deploying EDGE is roughly eight times that of GPRS. As the timeline for 3G has been brought forward to the end of 2001, this has further squeezed EDGE out of the market. Consequently, vendors are increasingly positioning EDGE as a niche commodity aimed at non-3G license winners and as a complementary service to 3G city networks. EDGE will eventually deliver data rates similar to the initial speed of 3G, and EDGE will be a viable alternative for those operators that do not secure 3G spectrum.

However, as the license awards progress throughout Europe it is becoming unlikely that any existing GSM operators will fail to secure a 3G license. The Yankee Group anticipates that nationwide 3G networks will roll out quickly so that operators can speedily recoup the high investment of obtaining 3G licenses. For these reasons, the Yankee Group believes that EDGE deployments will be insignificant.³¹ Yankee forecasts that by 2005 there will be only eight to ten EDGE deployments in Europe. The size of the EDGE infrastructure market in the next five years is unlikely to exceed \$4.5 billion in Europe.³¹

Wireless Application Protocol (WAP) and Simple Message Service (SMS)

Getting a wireless handset to tap into the Internet takes some finagling, because just about everything on a wireless device is diminutive compared to a PC—memory, processing, power supply, keypad and screen. In addition to the problems of engineering the individual devices, there's also the issue of enabling the dozens of different models to talk to each other. To attack that problem, Ericsson, Motorola, Nokia and Phone.com (formerly Unwired Planet) teamed up in 1997 to craft a new standard, called wireless applications protocol (WAP). The goal of the so-called WAP Forum was to develop a universal, open specification to bring the Web to the tiny screen. They succeeded in many ways. More than 100 companies are participating in the WAP Forum; a growing number of servers and handhelds incorporate WAP 1.1. One result, observes Yvonne Verse, a WAP Forum board member from Motorola, is that consumers can now buy any device and not worry about compatibility³⁷.

More recently, WAP has made possible access to Web sites with a level of security adequate for many consumer transactions. In the fourth quarter of 1999, a number of European operators including Orange (UK), Esat Digifone (Ireland), and Sonera (Finland) launched commercial WAP services. The first half of 2000 has witnessed the rollout of a number of commercial WAP services and mobile portals. However, WAP-enabled handset penetration is low. Handset availability has probably been the largest inhibitor to WAP. WAP will not realize its potential until GPRS is launched, for a number of reasons. With GPRS, speed of service will increase significantly, additional content will be available, and prices of handsets are likely to decrease (this may equate to a GPRS handset costing the same as a WAP handset does at this time). In Japan, NTT DoCoMo is experiencing network capacity overload due to the take-up rate of its i-mode service. The i-mode service has over 7 million subscribers. More significantly, these data services have stimulated voice traffic and average voice minutes per subscriber per month has increased by approximately 20% on NTT DoCoMo's network. The i-mode service has partnered with over 600 content providers, and it is widely acknowledged that this is one of the main reasons for its success.

SMS has been an encouraging demand indicator for data traffic. It has experienced exponential growth in the past 18 months. In the Italian market, which has the highest penetration in Europe

excluding the Nordic countries, SMS usage is high. Sonera in Finland claims 60% of its subscribers regularly use SMS. Esat Digifone in Ireland reported recently that prepaid customers were sending on average 30 SMS messages per customer per month, and Telecel in Portugal recently announced a 900% increase in the average number of SMS messages sent per month since October 1999. The largest growth in SMS has been in the prepaid market, which is where the majority of residential users including the youth market can be found. Initially business users are expected to be early adopters and high users of HSD services. However, SMS demand indicates that residential users will also be fast adopters.

Third Generation (3G) Overview

Various new standards have been proposed and alliances formed to promote third-generation wireless standards, termed 3G standards. These standards are for interoperable support of higher-speed data and multimedia services and additional capacity over existing 2G systems. Industry leaders expect more people to access the Internet and use electronic commerce from small, portable and palmtop devices. In addition, new operating systems are under development to support these trends.³⁸

The original concept for third-generation wireless systems emerged from an International Telecommunications Union (ITU) initiative known as the future public land mobile telecommunication system (FPLMTS). Throughout the 1990s, the ITU advanced the concept of a wireless system that would encompass technical capabilities a clear step above those of second-generation cellular systems. The current name for the third-generation system is International Mobile Telecommunications-2000 (IMT-2000). The number refers to an early target date for implementing the new technology and also the frequency band (around 2000 MHz) in which it would be deployed.

As envisioned in the IMT-2000 project, the third-generation wireless system would have a worldwide common radio interface and network. It would support higher data rates than do second-generation systems yet be less expensive. It would also advance other aspects of wireless communications by reducing equipment size, extending battery life, and improving ease of operation. In addition, the system would support the services required in developing as well as developed nations. Since 1990 IMT-2000 recommendations have been approved that elaborate on the initial goals, establish security principles, prescribe a network architecture, present a plan for developing nations, establish radio interface requirements, and specify a framework for a satellite component. The ITU anticipated an international competition leading to a radio interface that could be developed and deployed by the year 2000. The competing radio interfaces would provide minimum outdoor data rates of 384 Kbps and an indoor rate of 2 Mbps. Other than providing a forum for discussion of standards proposals, the ITU has not adopted clear plans of how to proceed beyond the point of reviewing the proposals. The 1995 World Radio Conference set aside spectrum for nations to consider for the deployment of IMT-2000. The bands are 1920-1980 MHz and 2110-2170 MHz for terrestrial communications and 1980-2010 MHz and 2170-2200 MHz for satellites. As noted in Table 1-4 and Table 1-5, the United States has already allocated spectrum bands to personal communications that include part of the lower IMT-2000 band, making it unlikely that U.S. service providers could deploy IMT-2000 at all. Early on, attention to the ITU work was limited in both Europe and the United States, where growth in second-generation digital cellular and personal communications markets has been strong. It was the Japanese, virtually alone among all nations, who insisted that the ITU program proceed as fast as possible because they were running out of spectrum for their cellular and personal communications systems.

3G European Telecommunications Standards Institute (ETSI) members reached a consensus agreement for a third-generation (3G) mobile phone standard on January 29, 1998. This standard is a Universal Mobile Communications System (UMTS) solution called UTRA, UMTS Terrestrial Radio Access, that draws on both wideband-Code Division Multiple Access (WCDMA) and Time Division Multiple Access-CDMA (TD-CDMA) proposals. W-CDMA will be used for wide-area applications while TD-CDMA will be used primarily for low mobility indoor applications. This standard is expected to create a global market, and to be the widest third-generation standard in use.

3G will increase the data rate from 144 Kbps to 384 Kbps, eventually up to a theoretical limit of 2 Mbps. The first 3G systems are being built in Japan³⁹ and in the Isle of Man⁴⁰ (United Kingdom) in 2001. Europe and Asia will follow with the rollout of 3G technology between 2002 and 2003. In the United States, 3G licenses will be auctioned in 2002 with subsequent build out afterward.

With service demand as yet unproven, bidding wars have been occurring across Europe for UMTS licenses. So far, Finland, Spain, and the UK have awarded 3G licenses. The UK was the first country in Europe to hold a UMTS auction and raised \$37 billion, more than 10 times the original revenue forecast by the government. We expect the total cost of 3G for some domestic operators will be as high as \$12 billion (figure includes license cost and network build only), indicating great confidence that demand for NGD will be enormous.³¹

Some new capabilities and services introduced in 2.5G must be brought forward into 3G:

- Over-the-air programming
- Circuit Switched Data
- Mobile originated and broadcast SMS
- Multi-band operation
- International capabilities
- Wireless Intelligent Network

Politics - Government Backing

Strong political influences are at work in the introduction and regulation of 3G mobile telephony. Governments in Japan, the United States and Europe are strongly backing their native companies. It has not gone unnoticed by Japan and the United States that Europe has had a great deal of commercial success with the GSM standard both within and outside Europe. Governments also have an important role in the issuing and licensing of the frequency spectrum.

Spectrum Availability and Allocation

Radio spectrum around 2GHz has been set aside for 3G use by the International Telecommunications Union (ITU). Discussions are ongoing about the total amount of spectrum required for the new data-enabled services. The ITU believes that 330MHz will be required, but other organizations (including the UMTS forum) believe this bandwidth will support only about two-thirds of the expected requirement. The important issue is the spectrum available to each operator. This is particularly important for applications such as video that will use higher bandwidth. Lack of bandwidth will restrict the type and number of subscribers that the operators will be able to support. As spectrum is a scarce resource, some governments have seen this as an opportunity to garner additional revenue. The high price of the "entry ticket" has been a shock to

all participants, and will have a direct effect on shareholders' return on investment. This, in turn, will reduce the resources available for infrastructure R&D and equipment spending.

Standards

A number of organizations are involved in setting standards. This is a key area for 3G technology as part of the success of the 2G GSM standard can be attributed to the harmonization of the GSM standard by the European Telecommunications Standards Institute (ETSI) within Europe. With 3G mobile technology, the efforts at harmonization rest with the ITU as the final authority for the adoption of global standards. In Europe, the 3G standard is UMTS, which was developed by ETSI. It is based on the IMT-2000 "family of systems" concept. The ETSI proposal to the ITU is UMTS Terrestrial Radio Access (UTRA). This includes wideband code-division multiple access (W-CDMA) and the time-domain CDMA (TD-CDMA) hybrid variants.

The not-inconsiderable task of the ITU is to rationalize and harmonize the proposals from Europe and the other global regions. The Third-Generation Partnership Project (3GPP) was established to reconcile the various proposals based on the W-CDMA interface. The group is specifically interested in 3G mobile systems based on evolved GSM core networks. A parallel group (3GPP2) was established around the U.S.-based cdma2000 proposal. The next step in harmonization came in 1999 when a group of operators (the Operator Harmonization Group [OHG]) proposed a reconciliation of the 3GPP and 3GPP2 groups' ideas in a proposal dubbed Global Third Generation (G3G) standard to allow interoperability between UTRA and cdma2000. The G3G standards are as follows:

- Time-division duplex CDMA (TD-CDMA)
- Direct-sequence CDMA (W-CDMA, or CDMA2000)
- Multicarrier CDMA (CDMA-MC), evolved from cdma2000

The results of this continuing harmonization process suggest that the G3G concept with the three modes above will be promoted as a dominant global standard. It is likely that DS-CDMA will be the popular mode with European operators, with TDD-CDMA being used for picocells in offices or similar environments. It should be noted that the concept of 3G is to provide more than merely an improved cellular system. Its aim is to integrate networks, including satellite, terrestrial cellular and cordless systems, with seamless roaming.

Table 3-5 demonstrates 3G rollout plans. In the US, AT&T said it plans to deploy what it terms "true" 3G (third generation) services beginning in 2002, providing even faster data speeds with EDGE (enhanced data rates for GSM evolution) technology. In addition, AT&T Wireless will deploy UMTS (universal mobile telecommunications system)-based 3G systems starting in 2003.⁴¹

Country	Operator	CDMA2000 Trial/Launch Date
Australia	Telstra	Trial 3Q 2000
Brazil	Global Telecom	Launch 4Q 2001
Brazil	Telesp Celular	Launch 4Q 2001
Brazil	Vesper	Launch 4Q 2001
Canada	Bell Mobility	Launch 4Q 2001
Canada	Telus Mobility	Trial 3Q 2000
Chile	SmartCom PCS	Launch 1H 2002
Japan	KDDI	Launch 1H 2002
Korea	KT Freetel	Commercial
Korea	LG Telecom	Commercial
Korea	SK Telecom	Commercial
Mexico	Pegaso PCS	Launch 4Q 2001
New Zealand	Telecom Mobile Limited	Launch 4Q 2001
Ukraine	CST Invest Limited	Launch 1Q 2002
United States	AirGate PCS	Launch 1Q 2002
United States	Alamosa PCS	Launch 1Q 2002
United States	ALLTEL Communications	Launch 2H 2001
United States	Horizon PCS	Launch 3Q 2002
United States	Sprint PCS	Launch 4Q 2001
United States	Verizon Wireless	Launch 2H 2001
Venezuela	Telcel	Trial 1H 2001
Vietnam	Saigon Postel	Launch 2H 2001

Table 3-5. 3G Roll-Out Plans⁴²

This table demonstrates the worldwide 3G rollout plans for major markets.

CDMA 2000

There were five terrestrial standards developed as part of the IMT-2000 program. CDMA2000 1X, like CDMA2000 3X, is an ITU-approved, IMT-2000 (3G) standard. It is part of what the ITU has termed IMT-2000 CDMA MC (multicarrier), and was sanctioned along with four other terrestrial IMT-2000 standards when ITU-R completed the Recommendations in late 1999. For further information, visit the ITU web site at http://www.itu.int/imt/what_is/roadto/index.html.

The evolution to CDMA2000 3G services is not limited to current cdmaOne operators. CDMA2000 is extremely attractive for TDMA operators because they already use the same core network as cdmaOne operators. For GSM operators, the CDMA-MC to GSM MAP standard (IS-833) defines how the CDMA2000 air interface can operate on the GSM MAP network, making this a technically feasible and economical approach to offering 3G services in a timely manner. In addition to mobile applications, CDMA2000 may also be deployed in a fixed wireless local loop (WLL) environment.

CDMA2000 3G services have already been commercially deployed, making the IMT-2000 vision a reality. SK Telecom (Korea) launched the world's first commercial 3G system in October 2000, and has realized data rates of over 150 kbps, exceeding the 144 kbps required by the IMT-2000 standard. LG Telecom and KT Freetel (Korea) launched CDMA2000 service in the spring of 2001. There will be additional CDMA2000 commercial rollouts in Asia, Latin America and North America later this year. Figure XXX below shows the trial and launch plans for those operators who have announced their intentions to offer CDMA2000 services thus far.⁴²

CDMA2000 is not constrained to only the IMT band; it is defined to operate in all existing allocated spectrum for wireless telecommunications, thereby maximizing flexibility for operators.

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Furthermore, CDMA2000 delivers 3G services while occupying a very small amount of spectrum (1.25 MHz per carrier), protecting this precious resource for operators. These bands include: 450 MHz, 700 MHz, 800 MHz, 900 MHz, 1700 MHz, 1800 MHz, 1900 MHz, and 2100 MHz.

W-CDMA (also called CDMA2000 3X) is one of the components of UMTS, along with TDMA & cdma2000. It has a 5MHz air interface and is the basis of higher-bandwidth data rates. WCDMA is the radio interface technology for UMTS networks. It facilitates high capacity, multiple simultaneous services and truly high bit rates up to 2Mbit/s. A 3GPP-compatible open system right from the outset, WCDMA solution enables smooth evolution along with 3G standards. Open interfaces mean that you are not restricted to one supplier when expanding your 3G network.

CDMA2000 3X is a 3G technology that offers voice and data on a 5 MHz carrier (or 3 times the 1.25 MHz carrier). Also referred to as W-CDMA.

CDMA2000 1xEV – Evolution of CDMA2000 1X. 1xEV-DO (Data-Only) uses a separate 1.25 MHz carrier for data and offers peak data rates of 2.4 Mbps. 1xEV-DV (Data-Voice) integrates voice & data on the same carrier.

Universal Mobile Telephone Standard (UMTS) - Proposed data rates of <2Mbps, using combination TDMA and W-CDMA and will operate around 2GHz of spectrum. UMTS is intended to replicate the commercial success achieved a decade earlier with GSM.

Applications

With a variety of wireless services available, compelling applications are needed to drive the rollout of 3G services. Today, a variety of wireless services are available. Wireless portals provide information and services such as general news, business and financial information, traffic and travel services, Short Message Service (SMS) and e-mail. Table 3-6 provides an overview of how these services will evolve and what new services will be enabled by 2.5G and 3G technology.

Even as the number of wireless users grows, a new awareness is setting in. "Companies are beginning to see that wireless or mobile commerce won't happen just because of the proliferation of wireless devices," says John Distefano, leader of Cap Gemini Ernst & Young's mobile commerce practice. Only 2 percent of mobile phone users pay for monthly data services, according to The Yankee Group, largely because downloading data onto a tiny screen is such a painful process. Forrester Research Inc.'s recent survey of executives at U.S.-based billion-dollar companies indicates that only 9 percent have implemented any sort of wireless component to their business, while more than 50 percent were still in a wait-and-see mode, and some had no plans to pursue the technology at all. Therefore, companies that sell wireless-related services to businesses admit to a slowdown in the wireless revolution. "You hear the exact same story at every company," says Reason CEO Jeff Kohler, "and it usually comes from the CFO--they're dealing with five service companies, 15 approved devices, and 50 rate plans, and no one knows how much money they're spending on wireless."⁴³

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Type of Content	Consumer Applications	Business Applications
Information	<ul style="list-style-type: none"> • Reference content (e.g., maps) • Information updated dynamically • Location-sensitive information 	<ul style="list-style-type: none"> • Data collection • Data monitoring • Alerts
Communication	<ul style="list-style-type: none"> • Messaging • Enhanced and multimedia messaging 	<ul style="list-style-type: none"> • Calendar • Messaging • E-mail • Groupware
M-Commerce	<ul style="list-style-type: none"> • Retail • Financial and banking services • Payments 	<ul style="list-style-type: none"> • CRM • Sales • Field services
Entertainment	<ul style="list-style-type: none"> • Games and gambling • Audio • Video 	

Table 3-6. The Evolution of Wireless Services⁴⁴

The types of content promised for business and consumers enabled by future 3G systems are listed. The success of these types of services are yet to be demonstrated in the market.

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SECTION 4: TRANSITION FROM FIRST- TO SECOND-GENERATION SYSTEMS

This section is a discussion of the technological diffusion from first- to second-generation systems. Subscriber data is interpreted for regional and worldwide markets. Regional political influences are discussed to highlight the path dependence in various markets. Finally, a market diffusion model is fitted to the historical subscriber data to provide insight into the competitive dynamics in the wireless communications industry.

Diffusion and Market Data

The wireless industry has experienced exponential growth during the late 1990s. Figure 4-15 is a plot of worldwide analog and digital wireless subscribers. As can be seen in the plot, digital subscribers surpassed analog in 1997. The numbers of worldwide analog subscribers peaked in 1998 near 95 million subscribers, and have since proceeded to decline significantly. Digital subscribers have continued to grow at an exponential rate. Taking advantage of the dual-mode capabilities of most digital capable handsets, these digital subscribers will continue to use the legacy analog network where digital coverage is weak or non-existent.

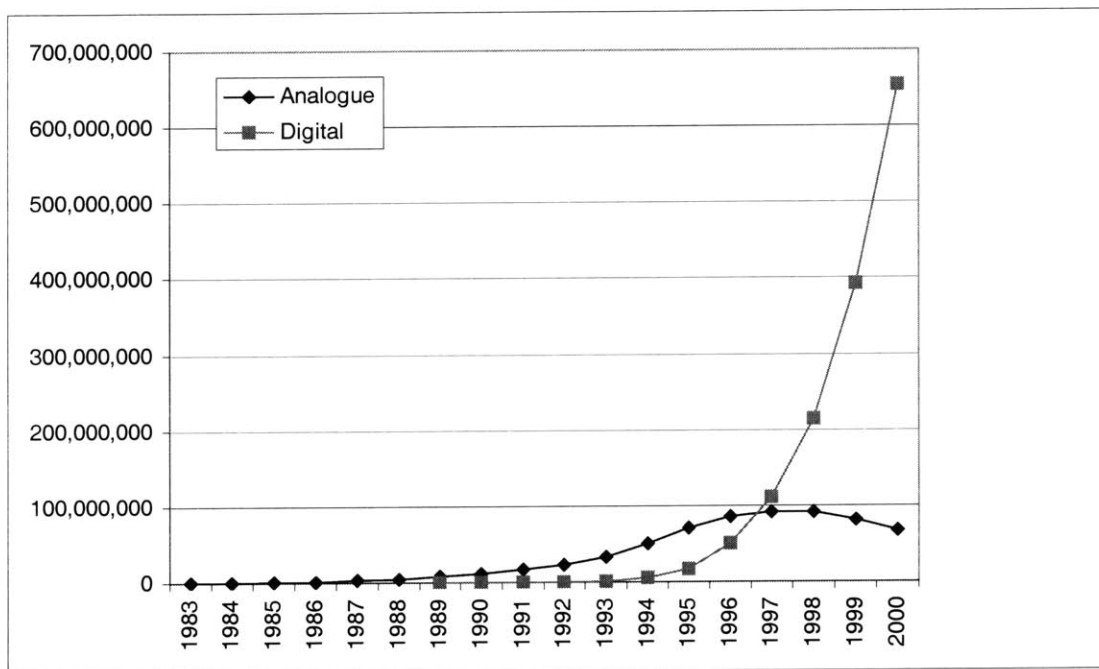


Figure 4-1. Worldwide Analog and Digital Wireless Subscribers²⁹

Digital subscribers surpassed analog in 1997. The numbers of worldwide analog subscribers peaked in 1998 near 95 million subscribers, and have since proceeded to decline significantly. Digital subscribers have continued to grow at an exponential rate. The subscriber data presented in figure 4-15 resembles the market response expected from classic technology “S-curve” theory. With 2G technology surpassing the performance of 1G technology, a “technological discontinuity” is evident, and with the ultimate success of 2G technology in the marketplace the visible response.

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The subscriber data presented in figure 4-1 resembles the market response expected from classic technology “S-curve” theory. With 2G technology surpassing the performance of 1G technology, a “technological discontinuity” is evident, and with the ultimate success of 2G technology in the marketplace the visible response.

Figure 4-2 plots the worldwide analog subscribers over time vs. each major standard. To understand this plot, one must remember that in North America and Japan, one analog standard was defined, AMPS and NTT (and later TACS), respectively. However, in Europe, the analog standard varied by geographic region. None of these European standards reached the dominance of the AMPS system. As can be seen, AMPS achieved a dominant position in the worldwide share of analog cellular subscribers. Even in the face of competition from higher performance second-generation (2G) systems, AMPS has maintained a significant subscriber base of in excess of 60 million subscribers at the end of 2000. This was enabled, in part, by the backward compatibility of most 2G North American cellular handsets to the AMPS system. This fact will be elaborated upon shortly.

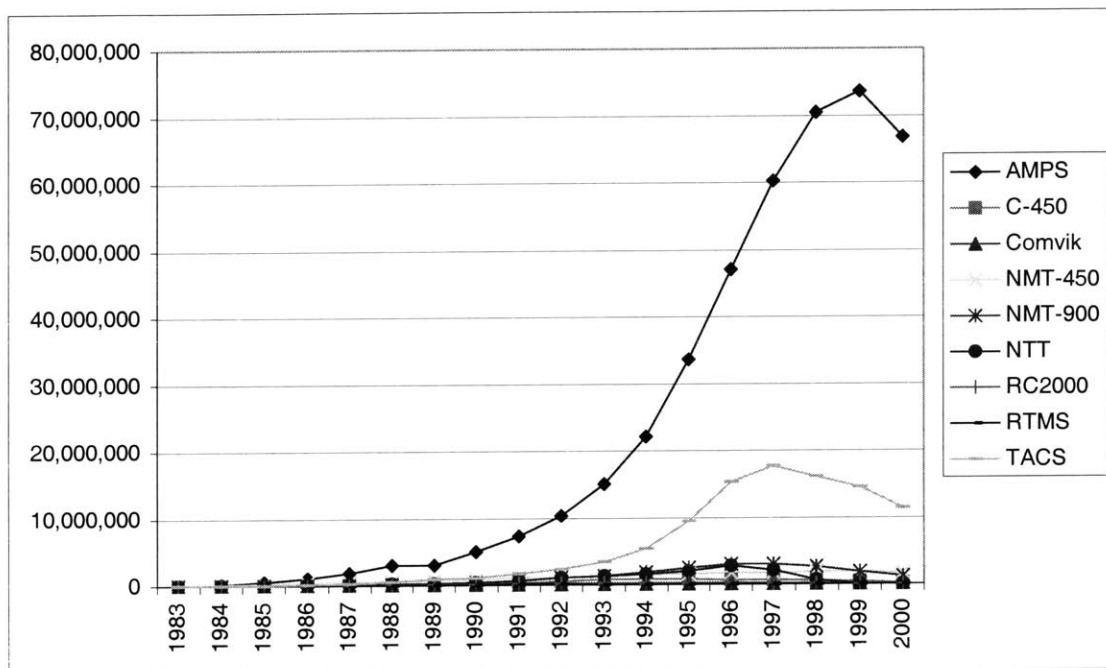


Figure 4-2. Worldwide Analog (1G) System Subscribers²⁹

This plot demonstrates the worldwide analog subscribers over time vs. each major standard. In North America and Japan, one analog standard was defined, AMPS and NTT (and later TACS), respectively. In Europe, the analog standard varied by geographic region. None of these European standards reached the dominance of the AMPS system. AMPS achieved a dominant position in the worldwide share of analog cellular subscribers. Even in the face of competition from higher performance second-generation (2G) systems, AMPS has maintained a significant subscriber base of in excess of 60 million subscribers at the end of 2000.

Figure 4-3 demonstrates the worldwide market share of the primary 2G (digital) cellular technologies. GSM, the primarily European standard, is by far the market leader with over 450 million subscribers at the end of 2000. The two primarily competing North American standards, CDMA, and TDMA, have smaller market shares, and as will be seen shortly, have begun to give up market share to GSM in North America.

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Figure 4-4 depicts the market share of United States analog (AMP) and digital (CDMA, TDMA, GSM) standards. The individual market share for each 2G standard (CDMA, TDMA) did not exceed that of the AMPS analog standard until 2000. This is due in part by the fact that most 2G handsets in the U.S. market are “dual mode” or compatible with both a 2G standard and the legacy AMPS. This backward compatibility has allowed for a smooth transition from the AMPS system to a heterogeneous 2G system. When a 2G standard has insufficient coverage, it can switch to analog mode, most of the time without even notice of the user. Special note should be taken of GSM. A latecomer to the U.S. market, GSM is the worldwide standard, but only has a small but growing share of the U.S. subscriber base. Figure 4-5 creates a different view on this data by plotting the U.S. AMPS analog standard vs. all digital U.S. subscribers. This view shows that “digital” or 2G has the greatest market share of subscribers, and the 2G protocols are an aspect of the emerging “dominant design” for cellular systems. However, as figure 4-4 illustrated, there isn’t a single U.S. 2G standard, but three standards that are incompatible.

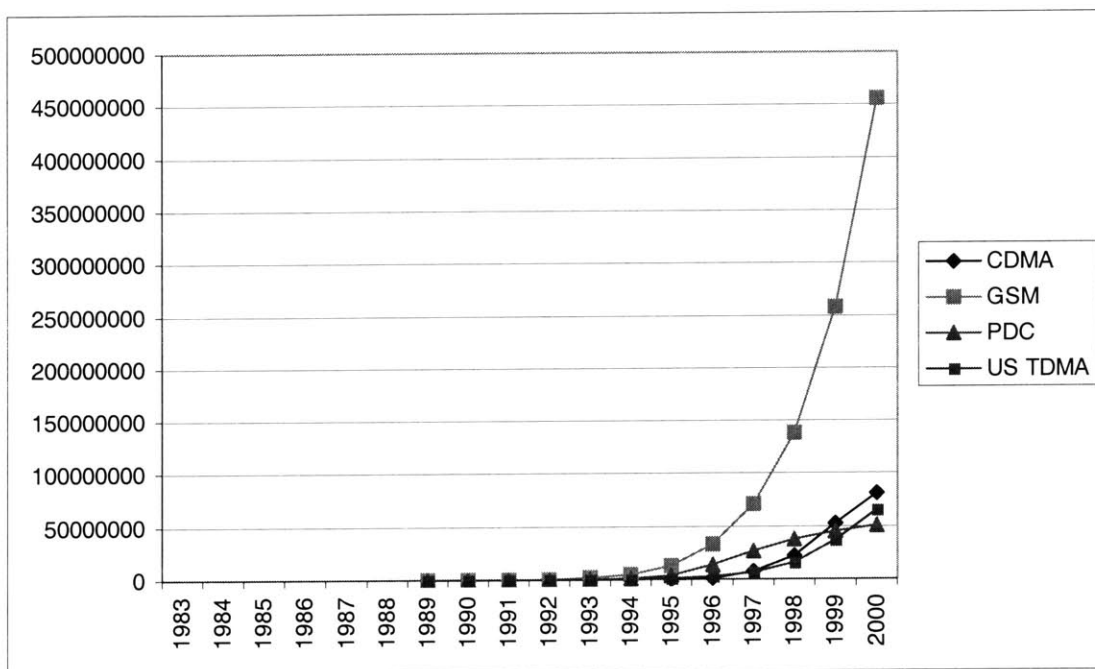


Figure 4-3. Worldwide Subscribers for 2G (digital) Technologies²⁹

GSM, the primarily European standard, is by far the market leader with over 450 million subscribers at the end of 2000. The two primarily competing North American standards, CDMA, and TDMA, have smaller market shares.

Figures 4-5 thru 4-10 depict the extent to which 2G wireless standards have displaced analog standards in other major international regions. Comparing the transition start times, it is obvious that the transition has taken longest in North America as a result of the evolution from one 1G standard to several competing 2G standards. Europe and other major regions underwent much faster transitions to digital technology, typically with digital standards surpassing analog circa 1995 vs. 1998 for North America. In part, this can be attributed to the need for a unified standard in Europe to promote seamless roaming and economies of scale for equipment producers. Figures 4-11 graphically illustrate the evolution from one 1G standard to multiple 2G standards in North America.

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Similarly, Figure 4-12 illustrates the evolution from multiple 1G standards to a single 2G standard in Europe.

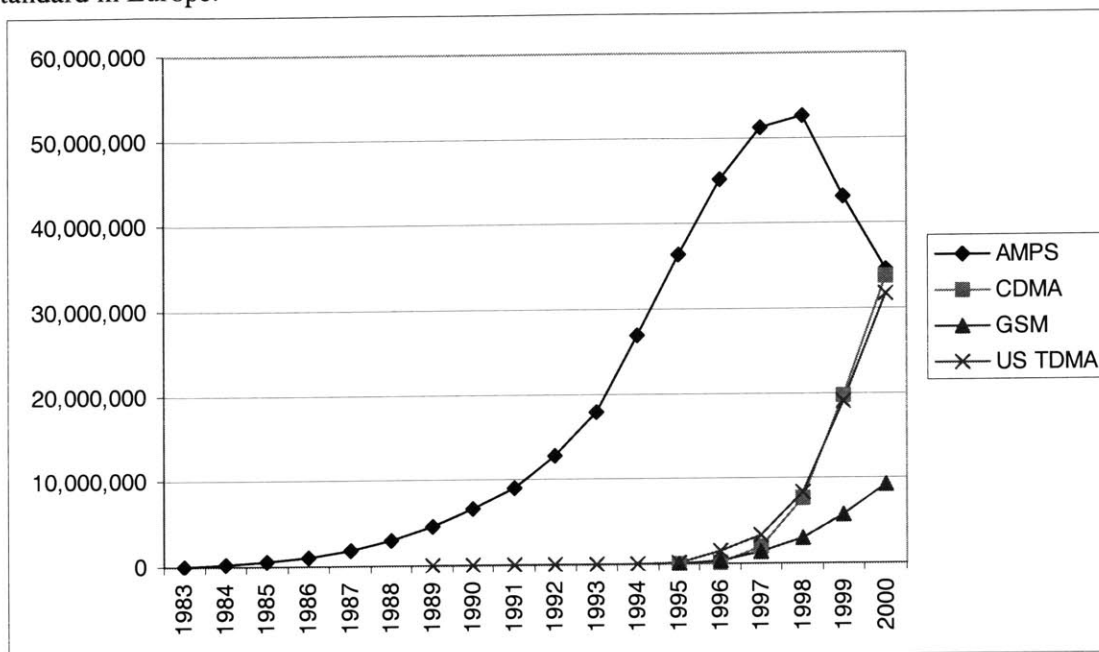


Figure 4-4. US AMPS vs. 2G Digital Subscribers (TDMA, CDMA, GSM) ²⁹

This figure demonstrates the market share of United States analog (AMPS) and digital (CDMA, TDMA, GSM) standards. The individual market share for each 2G standard (CDMA, TDMA) did not exceed that of the AMPS analog standard until 2000. This is due in part by the fact that most 2G handsets in the U.S. market are “dual mode” or compatible with both a 2G standard and the legacy AMPS. This backward compatibility has allowed for a smooth transition from the AMPS system to a heterogeneous 2G system.

As stated earlier, the early dominance of AMPS as a 1G standard helped to ensure the slow migration to 2G technologies in North America. This is partially illustrated by figure 4-13, a plot of the market share of major 1G standards as a percentage of the analog system total market share. As can be seen, AMPS achieved an early lead, surpassing 50% market share in 1985. Due to the tremendous “network effects”, a tipping occurred to AMPS in primary markets served by AMPS, installation of AMPS networks in European markets served by protocols with thin subscriber bases, and later, an acceleration to a unified 2G standard in markets that were artificially segmented by 1G standards below critical mass of subscriber base.

Figure 4-14 demonstrates the worldwide market share for 2G standards. Spurred by the numerous 1G standards in Europe, GSM entered the market several years earlier than other 2G standards with 100% market share. Due to regulatory barriers, GSM hasn’t faced any competition in Europe. As demonstrated by the data, it has achieved a remarkable dominant share of the worldwide market, and has recently reversed early gains made by the competing TDMA and CDMA standards. Network effects are again tipping the market toward a single GSM standard. However it should be noted that there are still four different frequency bands used throughout the world for GSM systems.

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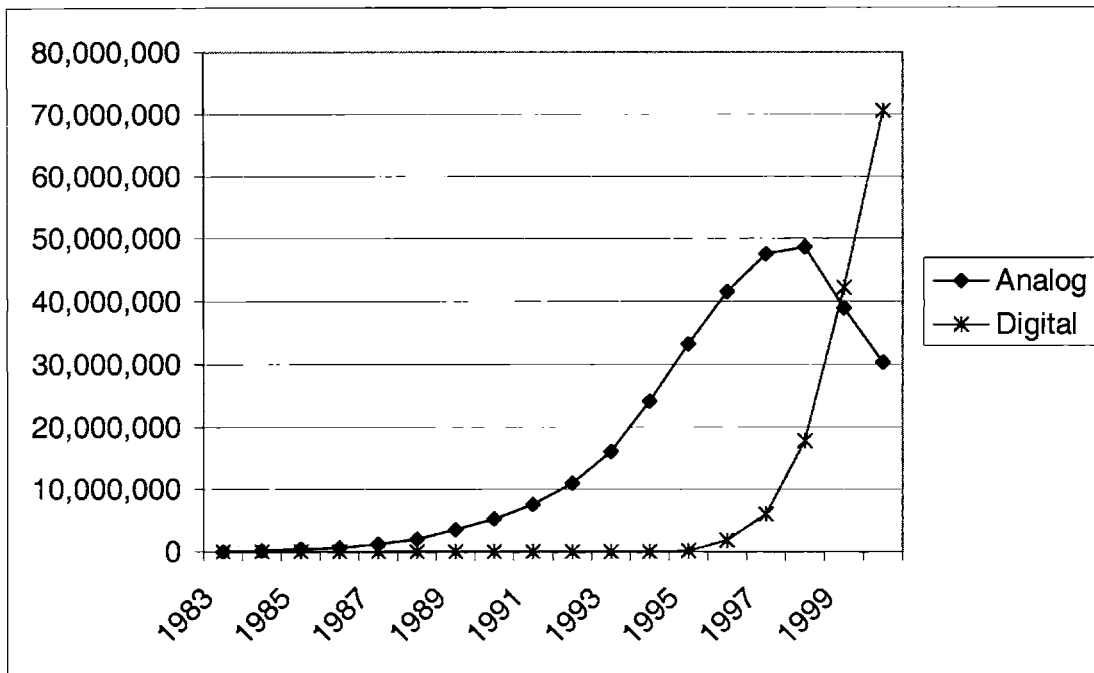


Figure 4-5. U.S. Analog vs. All-digital 2G Subscribers²⁹

This figure is another way to look at the data presented in figure 4-18. Here all the 2G standards (TDMA, GSM, CDMA) are consolidated into the digital curve. This total of 2G subscribers (digital) is compared to the subscribers of the 1G AMPS system. Total of 2G subscribers surpasses 1G subscribers in 1998.

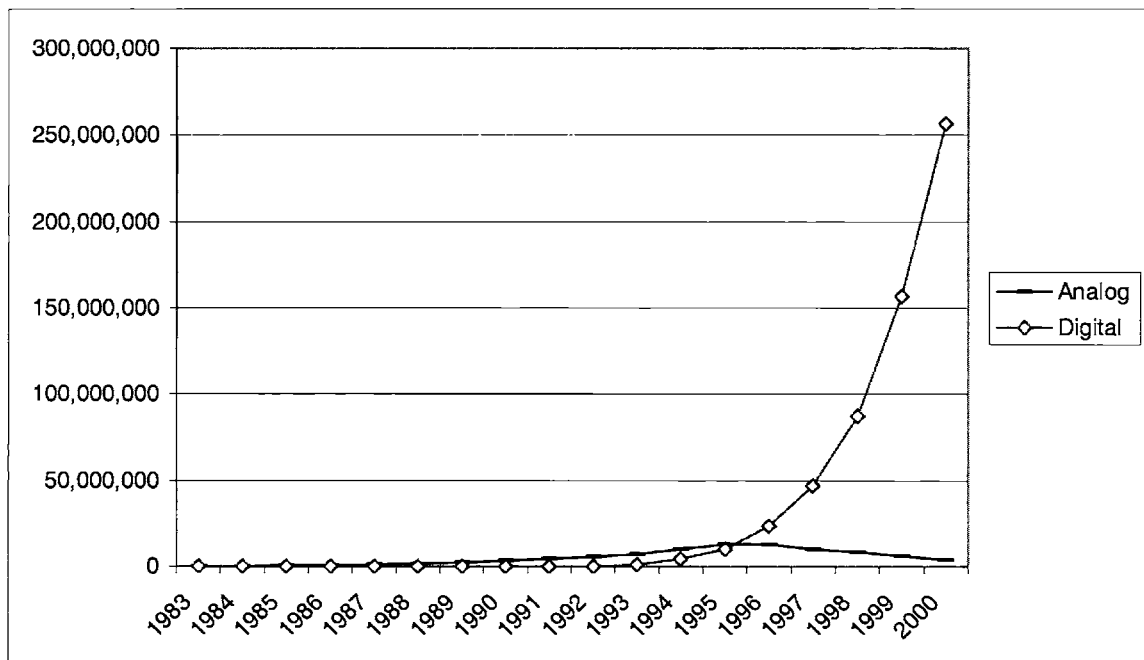


Figure 4-6. Western Europe Analog vs. Digital Subscribers²⁹

This figure compares all Western Europe 1G (analog) and 2G (digital subscribers). In comparison with figure 4-19, Western Europe's transition to 2G technology was sooner, and the 1G subscriber base did not achieve the same level as North America.

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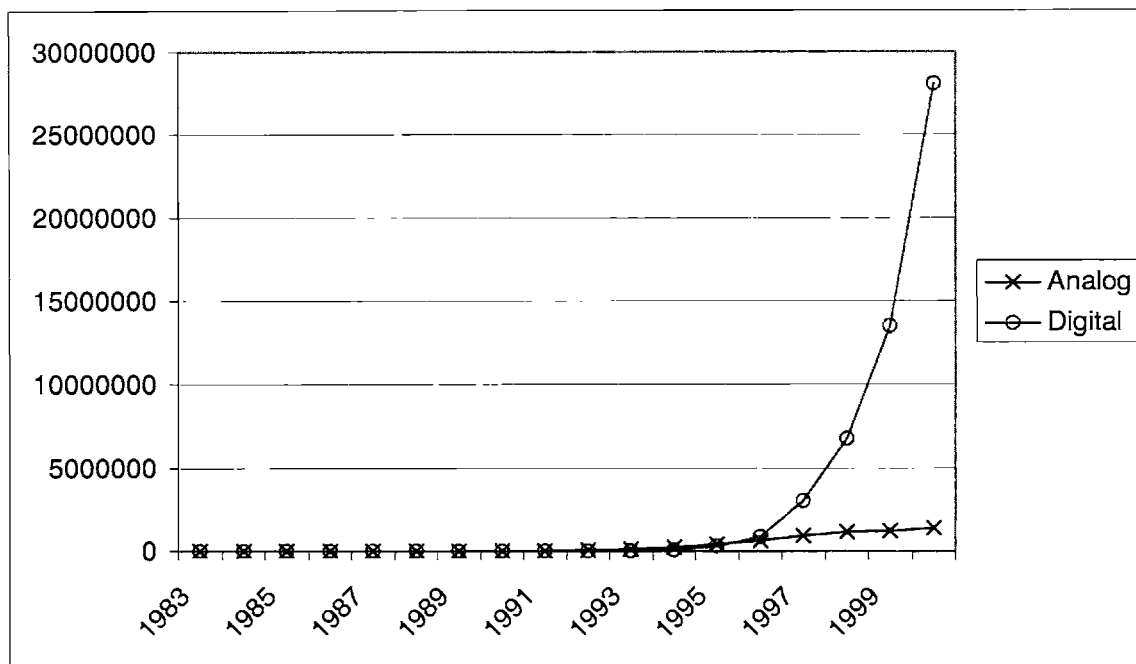


Figure 4-7. Eastern Europe Analog vs. Digital Subscribers²⁹

This figure compares all Eastern Europe 1G (analog) and 2G (digital subscribers). Similar to Western Europe, Eastern Europe's transition to 2G technology was sooner, and the 1G subscriber base did not achieve the same level as North America. However, the total subscribers in Eastern Europe are much less due to slower development of this technology in the former Soviet Bloc.

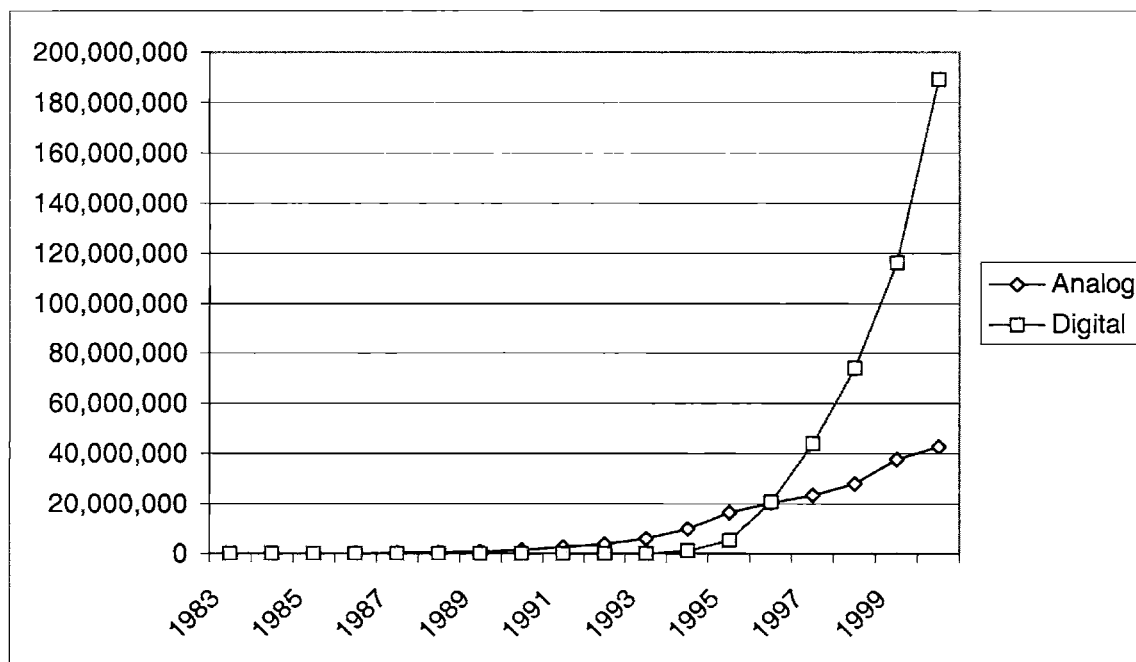


Figure 4-8. Asia Analog vs. Digital Subscribers²⁹

This figure compares all Asia 1G (analog) and 2G (digital subscribers). Compared with other regions Asia continues to grow analog subscribers, primarily in rural areas not well served by 2G networks.

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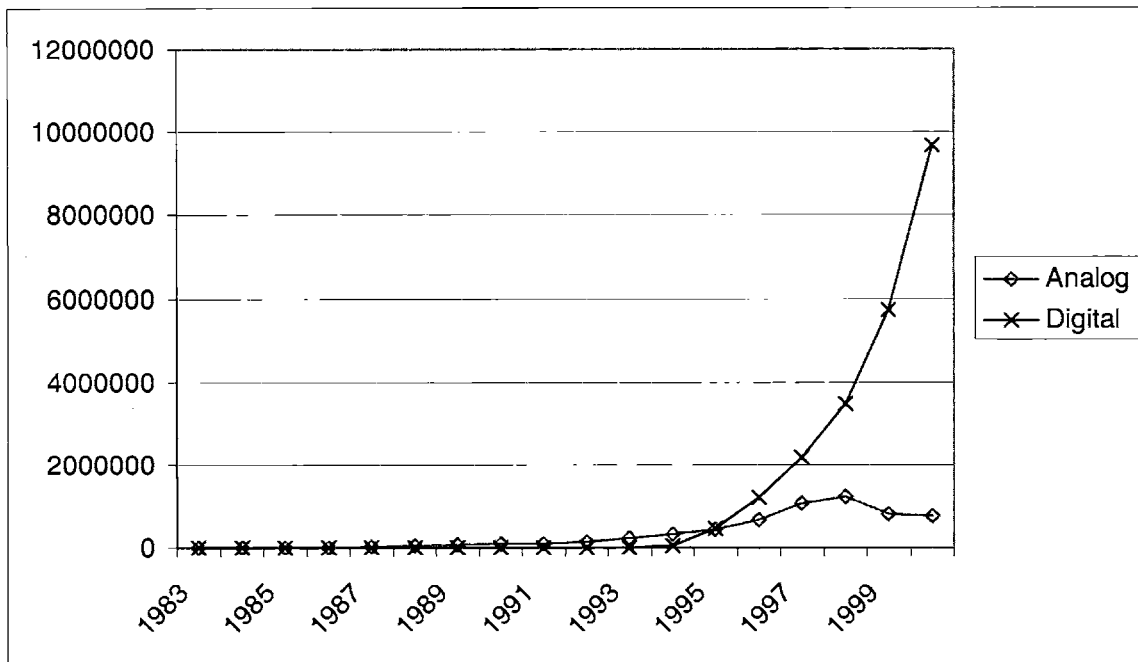


Figure 4-9. Middle East Analog vs. Digital Subscribers²⁹

This figure compares all Middle East 1G (analog) and 2G (digital subscribers). Similar to Western Europe, Middle East's transition to 2G technology was sooner, and the 1G subscriber base did not achieve the same level as North America. However, the total subscribers in the Middle East are much less due to slower development of this technology.

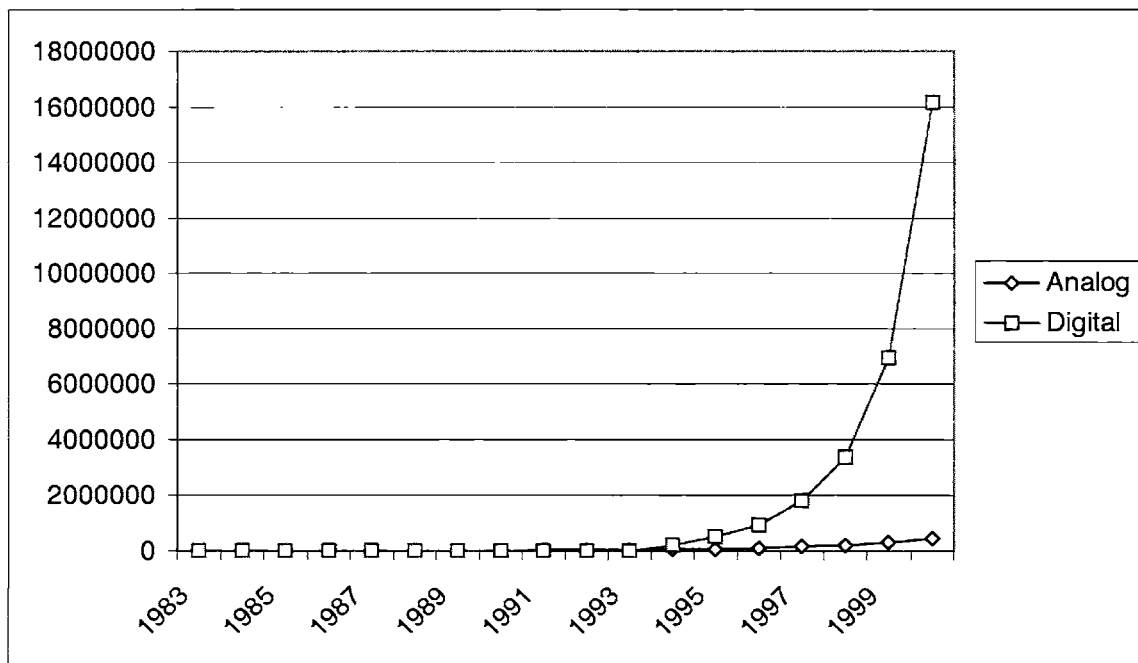


Figure 4-10. Africa Analog vs. Digital Subscribers²⁹

This figure compares all Africa 1G (analog) and 2G (digital subscribers). 1G technology did not have extensive development in Africa, with the main presence in South Africa.

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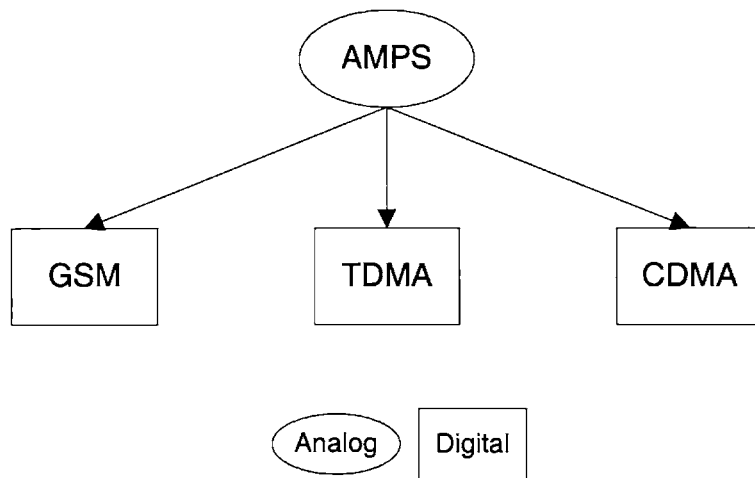


Figure 4-11. North American evolution from analog to digital standards²⁷
 This figure describes the evolution from 1G to 2G standards in North America. North America evolved from one analog standard to multiple second-generation 2G standards.

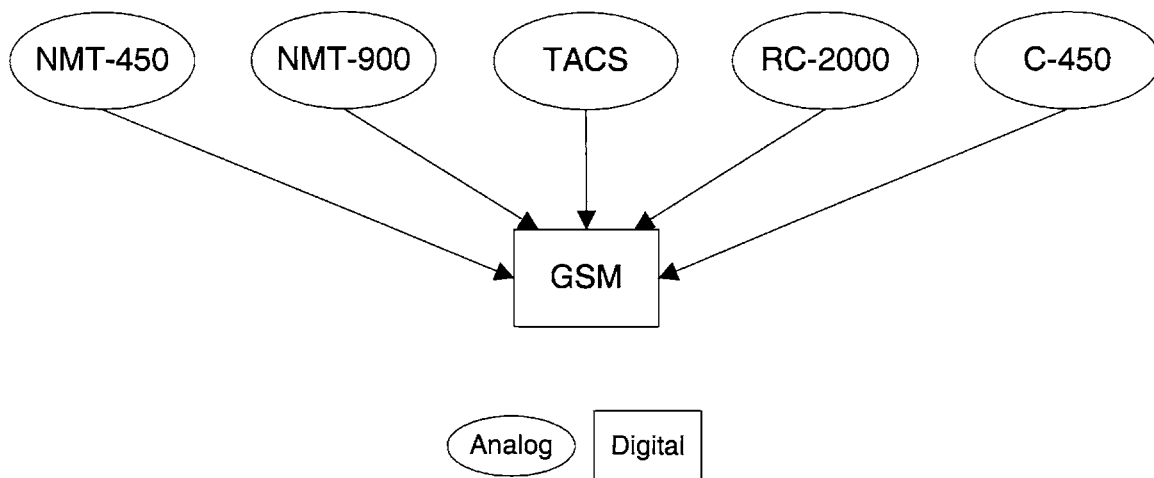


Figure 4-12. European Evolution from Analog to Digital Standards²⁷
 This figure describes the evolution from 1G to 2G standards in Europe. Europe evolved from multiple regional analog standards to a single second-generation 2G standard. This is in contrast to the North American experience demonstrated in figure 4-11.

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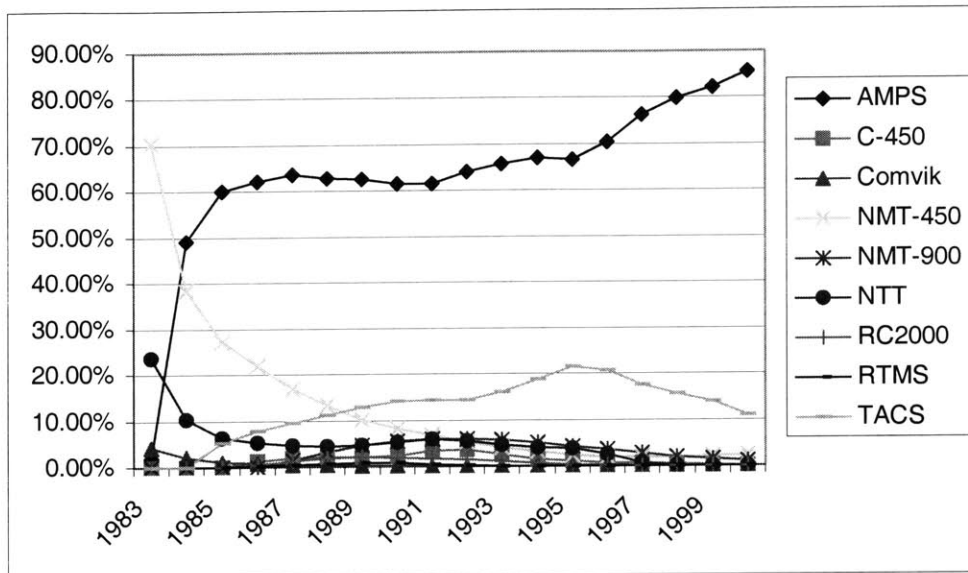


Figure 4-13. Analog Market Share of Worldwide 1G Standards²⁹

This figure further demonstrates the dominance of AMPS as a 1G standard. AMPS had an early greater than 60% worldwide 1G market share and has maintained or increased this share as the other 1G subscribers switched to newer 2G technologies. Of the remaining subscribers to 1G standards, AMPS maintains a greater than 80% market share.

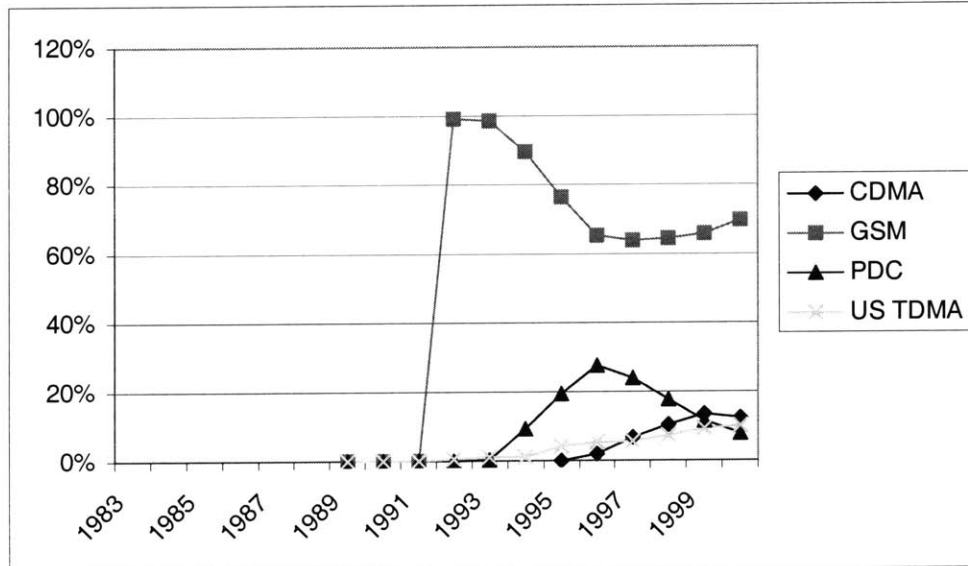


Figure 4-14. Digital Market Share of Worldwide 2G Standards²⁹

This figure demonstrates the worldwide market share for 2G standards. Spurred by the numerous 1G standards in Europe, GSM entered the market several years earlier than other 2G standards with 100% market share. Due to regulatory barriers, GSM hasn't faced any competition in Europe. As demonstrated by the data, it has achieved a remarkable dominant share of the worldwide market, and has recently reversed early gains made by the competing TDMA and CDMA standards.

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The worldwide market share is demonstrated in figure 4-15. Although at the end of 2000, 1G still had about 10% worldwide share, it's obvious that 2G is increasing at the expense of 1G. This is while the market penetration is increasing. Figure 4-16 shows the market penetration for several major markets (UK, US, and Japan). It's obvious that major markets penetrations are reaching 50%, and higher for the UK, while 2G is dominating the total installed base.

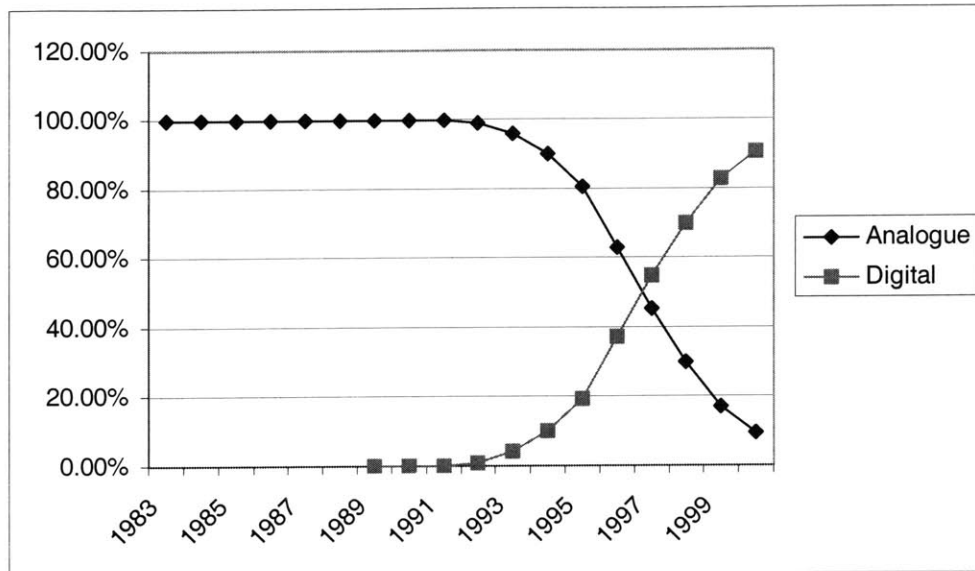


Figure 4-15. Worldwide Market Share Analog vs. Digital²⁹

This figure demonstrates the worldwide market share of all analog and all digital technologies. Although at the end of 2000, 1G still had about 10% worldwide share; it's obvious that 2G is increasing at the expense of 1G. This is while the market penetration is increasing.

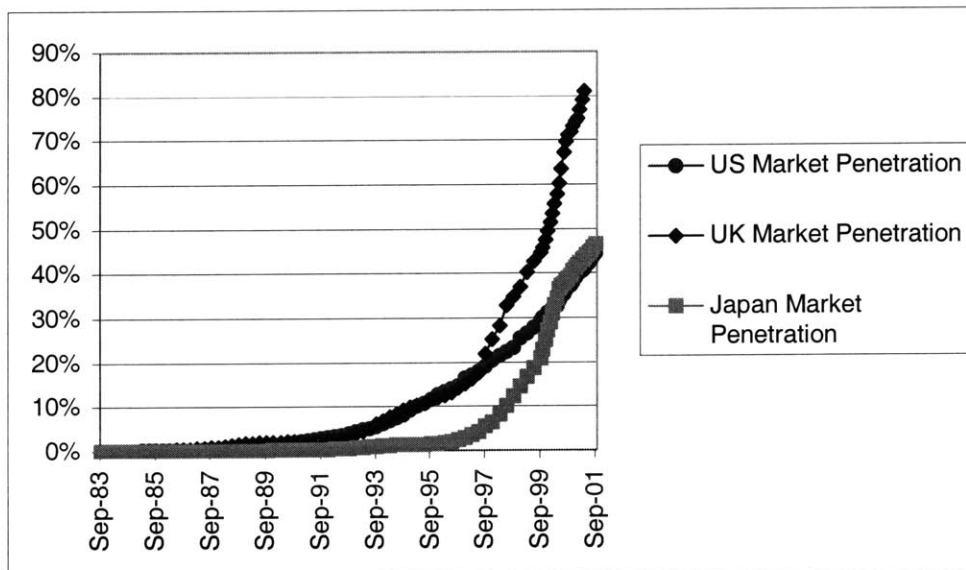


Figure 4-16. Cellular Market Penetration²⁹

This figure demonstrates the market penetration of all cellular technologies. Significant growth opportunities exist in many most major international markets.

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Political Influences in the Transition from 1G to 2G Technologies

Commercial wireless technologies have followed divergent evolutionary paths in different parts of the world. For example, strong contrasts are evident in the transition from first-generation cellular systems to second-generation systems in the United States and Europe. At first a single U.S. system was used for analog cellular communications, AMPS, and every cellular telephone in the United States and Canada could communicate with every base station. By contrast, European users were faced with a complex mixture of incompatible analog systems. To maintain mobile telephone service, an international traveler in Europe needed up to five different telephones.

The situation was reversed by second-generation systems. Now there is a single digital technology, GSM, deployed throughout Europe (and in more than 100 countries worldwide), whereas the United States has become a technology battleground for three competitors: GSM (PCS-1900), TDMA (IS-136), and CDMA (IS-95, cdmaOne). These evolution paths are illustrated in figures 4-11 and 4-12.

The differences in technology evolution are due in large measure to different government policies in Europe, the United States, and Japan, the world's principal sources of wireless technologies. Three types of government policies influence developments in wireless systems: policies on radio spectrum regulation, approaches to R&D, and telecommunications industry structure. The reasons for the shifts in the above example can be found primarily in changes in spectrum regulation policies adopted in the 1980s. In establishing first-generation systems in the United States in the late 1970s, the FCC regulated four properties of a radio system: noninterference, quality, efficiency, and interoperability.²³

In the 1980s, deregulation was in vogue and the scope of the FCC's authority was restricted to regulating noninterference; the other wireless system properties were deemed commercial issues to be settled in the marketplace. Although this policy stimulated innovation in the U.S. manufacturing industry, it also meant that operating companies had to choose among various competing technologies.

In Europe, the main trend in government regulation in the 1980s was a move from national authority to multinational regulation under the European Community (EC; now the European Union [EU]). The EC had a strong interest in establishing continental standards for common products and services, including electric plugs and telephone dialing conventions. In this context, the notion of a telephone that could be used throughout Europe had a strong appeal. To advance this notion, the EC offered new spectrum for cellular service on the condition that the operating industries of participating countries agree on a single standard. Attracted by the availability of free spectrum, operating companies (many of them government-owned) in 15 countries put aside national rivalries and adopted the GSM standard.

Therefore, a new pattern of technical cooperation was established in Europe. This cooperation was reinforced by the European Commission (the administrative unit of the EU), which funded cooperative precompetitive research focusing on advanced communications systems. A consortium of companies and universities performs the research. Spectrum management rules continue to prescribe a single standard for each service, meaning that an industry consensus is required before a standard is introduced. Once a technology is established, companies enter the competitive phase of product development and marketing.

This process promoted a thorough investigation of technologies prior to standardization and assures economies of scale when commercial service begins. In preparation for 3G, extensive R&D and evaluation of competing prototypes have been under way since 1994. All of this activity will provide European industry with a strong technical base for realizing the goals for mobile communications in the first decade of the next century.

The U.S. approach to communications technology R&D is much more competitive. Individual companies perform much of this research in the context of their product marketing plans. Coordination takes place within diverse standards organizations such as the Telecommunications Industry Association, IEEE, and American National Standards Institute.

For the most part, standard setting is a competitive rather than cooperative process in the U.S., with each company or group of companies striving to protect commercial interests. The FCC rules for spectrum management allow license holders to transmit any signals, subject only to constraints on interference with the signals of other license holders. Similar flexibility is extended to unlicensed transmissions. As a consequence, there are multiple competing standards (seven in the case of wideband personal communications) for wireless service in the United States.

Government policies on industry structure also strongly influence technology development. After the FCC issued cellular operating licenses, most of the companies that began offering cellular service had limited technical resources and relied almost entirely on vendors and consultants for technical expertise. Even the cellular subsidiaries of the regional Bell operating companies had to build a new base of expertise: Under the terms of the consent decree that broke up AT&T in 1984, these cellular companies had no access to the technical resources of Bellcore, the research unit of the regional Bell companies. In this environment, much of the new wireless communications technology in the United States has come from the manufacturing industry, with the result that proprietary rather than open network-interface standards have proliferated.

The published technical standards for wireless communications were at first confined to the air interface between terminals and base stations. Eventually the industry adopted a standard for intersystem operation to facilitate roaming. Many other interfaces, especially those between switching centers and base stations, remain proprietary but the situation is changing to allow fully open systems.

By contrast, the European cellular operating industry has been dominated by national telephone monopolies. These companies have strong research laboratories that participate fully in technology creation and standards setting. To gain the advantage of flexibility in equipment procurement, operating companies favor mandatory open interfaces, a preference reflected in the GSM standard.

Modeling 1G- to 2G-Technological Interaction

Using the subscriber data presented earlier in this section, a model⁵⁹ was fitted to the historical subscriber data to illustrate future technological interactions. The model is based on the Pistorius' and Utterback's work on a Lotka-Volterra model for multi-mode technological interaction. This model is a mathematical framework to model the multi-mode interaction with a general multi-technology solution. In the multi-mode framework, the effect that one technology has on another's growth rate is taken as the criterion whereby the mode of interaction is judged, and hence one can distinguish between symbiosis, pure competition and predator-prey interaction. The difference solution to the multi-mode technological interaction is modeled by the following solution that is easily implemented in a spreadsheet:

$$T_i(t+1) = \frac{e^{a_i} T_i(t)}{1 - \sum_{j=1}^J \frac{s_{ij} c_{ij} (e^{a_i} - 1)}{a_i} T_j(t)}$$

Using this framework, the mode of technological interaction can be identified. Pistorius and Utterback identified three modes of interaction: pure competition, symbiosis, and predator-prey. Pure competition is where both technologies have a negative effect on one another's growth. Symbiosis is where both technologies have a positive effect on one another's growth. Predator-prey is where one technology has a positive effect on the other's growth rate but the second has a negative effect on the growth rate of the first.

To illustrate regional differences as well as the affect of a larger worldwide market, three scenarios are simulated: worldwide 1G (analog) to 2G (digital) evolution, U. S. 1G to 2G (all three standards) evolution, and worldwide 1G to 2G (three competing standards) evolution. Comparison of these three predictions will help to illuminate the market dynamics that affect future 3G market, and the need for an innovation such as software defined radios. As will be discussed, all three models illustrate a pure competition mode of technological interaction.

The Lotka-Volterra models that are illustrated in the following were fit using a least-squares routine implemented in the Microsoft Excel spread sheet. Appendix A contains the three set of model parameters extracted using the historical data presented earlier in this chapter. In all three cases, the mode of technological competition that best fit the historical data is the pure competition mode.

Figure 4-17 shows the model for the worldwide 1G to 2G total subscribers. The first figure illustrates the Lotka-Volterra model fit. The best model fit was with a pure competition mode of technological competition. The model predicts an eventual decay of 1G technologies and a S-curve growth of total 2G technologies with an ultimate saturation of over 2 billion subscribers. In this formulation, there is ultimately a market dominance of the 2G technologies. It should be noted that the ultimate market size was not constrained in the process to limit the market size, but instead is based on the pure S-curve like competition inherent to the Lotka-Volterra formulation.

Figure 4-18 demonstrates the model for U. S. 1G to 2G subscribers. The first figure illustrates the Lotka-Volterra model fit. The model predicts an eventual decay of 1G technologies and a S-

curve growth of 2G technologies. The model predicts that of the three 2G technologies prevalent in the U. S. market, only TDMA and CDMA will dominant with GSM ultimately decaying with the 1G AMPS technology. Special note should be given to the GSM result and it should be compared to the result for worldwide competition in figure 4-19. In the U. S. ignoring other subscribers worldwide GSM doesn't look like it will survive. However as 4-19 illustrates, GSM already has, and will maintain a worldwide dominant position.

Figure 4-19 illustrates the model for worldwide 1G to 2G subscribers. The first figure illustrates the Lotka-Volterra model fit. The model predicts an eventual decay of 1G technologies and a S-curve growth of 2G technologies. The model predicts that GSM will maintain it's world wide dominant position ultimately achieving a level similar to that predicted in figure 4-17, and that TDMA and CDMA will maintain niche roles in the U. S. and other markets where they already have dominant positions. Special note should be given to the GSM result and it should be compared to the result for U. S. competition in figure 4-18. In the U. S. ignoring other subscribers worldwide, GSM doesn't look like it will survive. However, as 4-19 illustrates, GSM already has, and will maintain a worldwide dominant position.

Several technology management issues are highlighted from the model and it's predictions. The fact that the best model fit to the historical data is pure competition has implications to how to manage the transition to new technologies in the wireless industry. Pure competition could indicate that backward compatibility and compatibility with other 2G standards is not very important after a certain critical mass of subscribers and network deployment is achieved. As will be highlighted in the section on network technologies and gateway innovations, the need for a legacy capability, such as backward compatibility to a 1G network, usually has a finite lifetime. After it's lifetime, it is no longer needed and is eliminated due to its extra expense or complexity.

Comparing the three different markets illustrate the dynamics inherent in the wireless industry. Network effects and first mover advantages are evident. The competing technologies that gain a critical mass in a market are likely to survive, both regionally and worldwide. To determine the technological winner, the worldwide market may need to be assessed, not just the markets where major regional standards are competing.

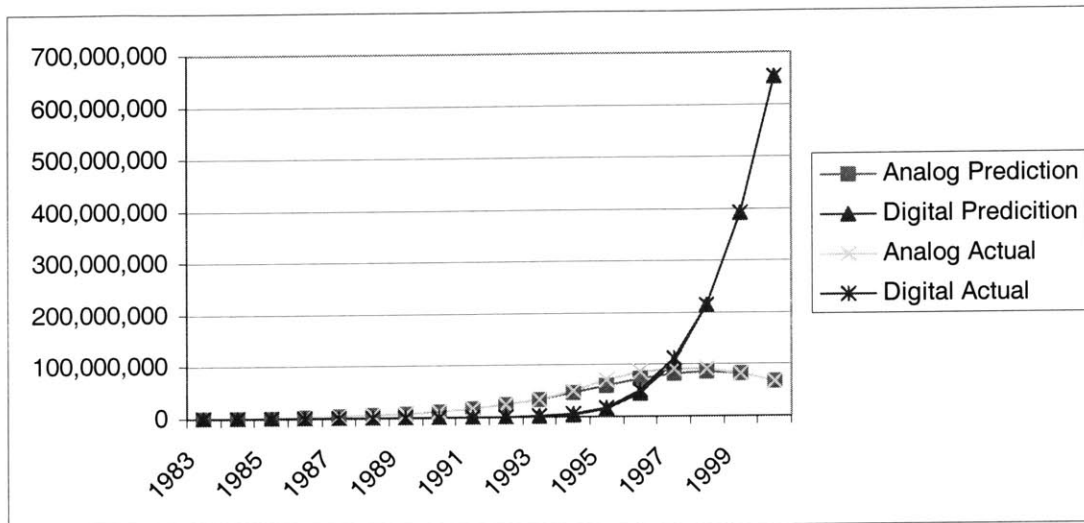
From the worldwide data, it seems likely that even though GSM is simulated to be a decaying technology in the U. S. market alone, it will be the dominant technology in the worldwide market. The simulation that GSM decays in the U.S. market therefore has to be assessed in this light. Using this frame of reference, it seems that not only will GSM not decay, but will also thrive as one of three 2G standards in the U. S. market due to the substantial economies of scale in base station and handset manufacturing.

It is evident from the data and simulations that 1G technologies are doomed to die, and therefore transition strategies should be incorporated in future network plans. These strategies and hypotheses have implications for the eventual 2G to 3G transition and the competition between the various standards vying for worldwide and regional dominance. Since on a worldwide basis GSM will be by far the dominant 2G-technology, it is likely that GSM evolutionary derivatives will be the winning 3G-technologies on a worldwide basis. This could indicate that W-CDMA and CDMA2000 derivatives are the likely dominant 3G technologies based on evolution of subscribers from 2G to 3G technologies exclusively.

The hypothesis that the mode of technological interaction is based on pure competition for the 1G to 2G transition, implies that the mode of interaction would be similar for the 2G to 3G transition. This implies that competing 3G technologies will compete with each other and the existing 2G

networks. During the transition period, it is likely that a gateway innovation is needed to provide a large enough network. However, it is likely that the legacy communication needed is between one 2G and one 3G technology. Based on the pure competition between competing 3G standards, there is less of a need for a compatibility device between multiple 3G standards. However, once a dominant 3G technology is established with a broad enough network to satisfy the needs of most users, the need for the backward compatibility or gateway innovation will not justify its added complexity and cost.

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This figure illustrates the fit of the technological interaction model to the historical market data. The parameters derived during this fitting were used in the prediction illustrated below.

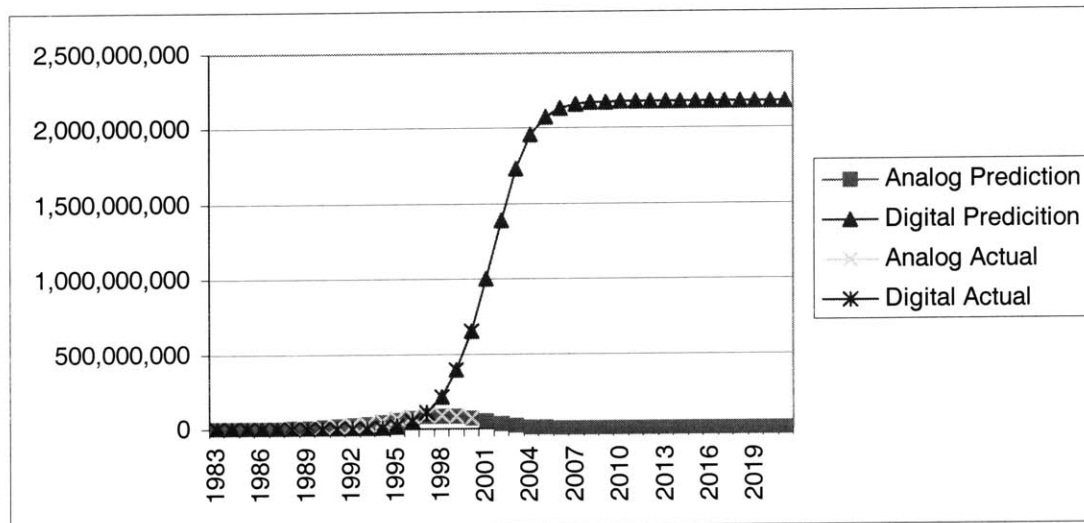
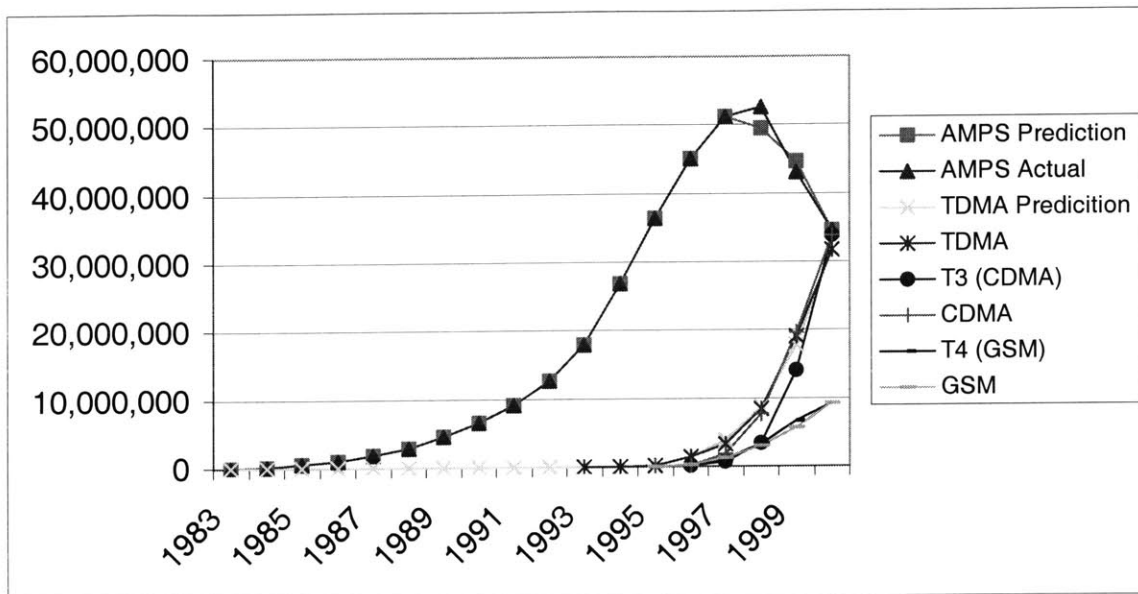


Figure 4-17. Worldwide 1G to 2G Model Prediction.

The model is based on a pure competition mode of technological interaction. The model predicts an eventual decay of 1G technologies and a S-curve growth of 2G technologies.

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This figure illustrates the fit of the technological interaction model to the historical market data. The parameters derived during this fitting were used in the prediction illustrated below.

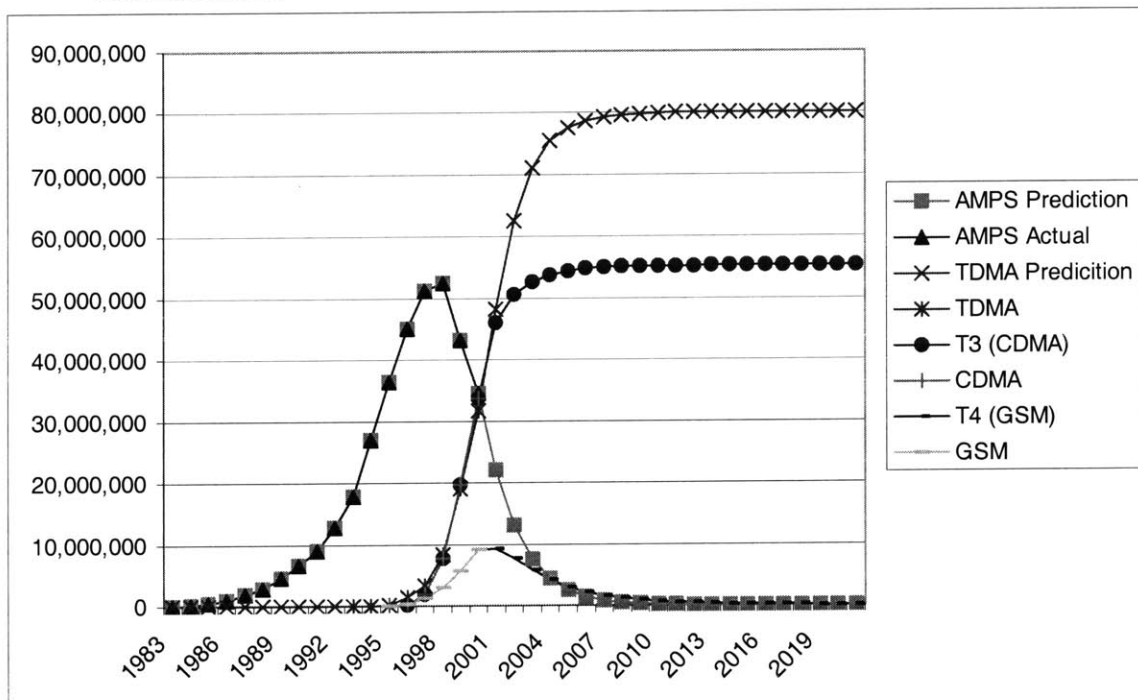
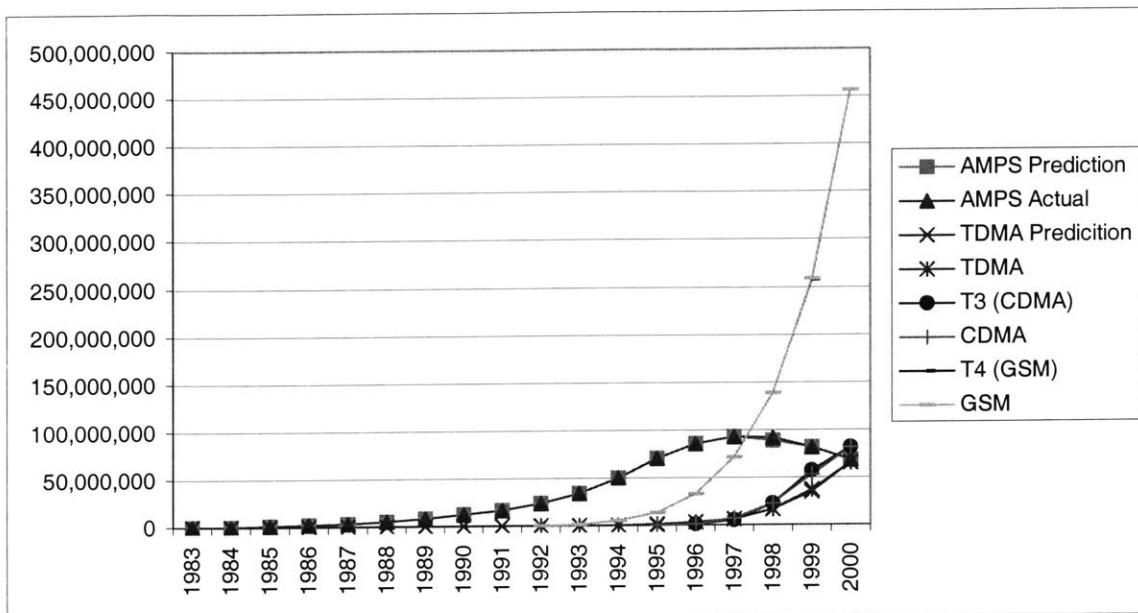


Figure 4-18. U.S. 1G- to 2G-Model Prediction.

The model is based on a pure competition mode of technological interaction. The model predicts an eventual decay of 1G technologies and a S-curve growth of 2G technologies. The model predicts that of the three 2G technologies prevalent in the U. S. market, only TDMA and CDMA will dominant with GSM ultimately decaying with the 1G AMPS technology. Special note should be given to the GSM result and it should be compared to the result for worldwide competition in figure 4-19. In the U. S. ignoring other subscribers worldwide GSM doesn't look like it will survive. However, as 4-19 illustrates, GSM already has, and will maintain a worldwide dominant position.

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This figure illustrates the fit of the technological interaction model to the historical market data. The parameters derived during this fitting were used in the prediction illustrated below.

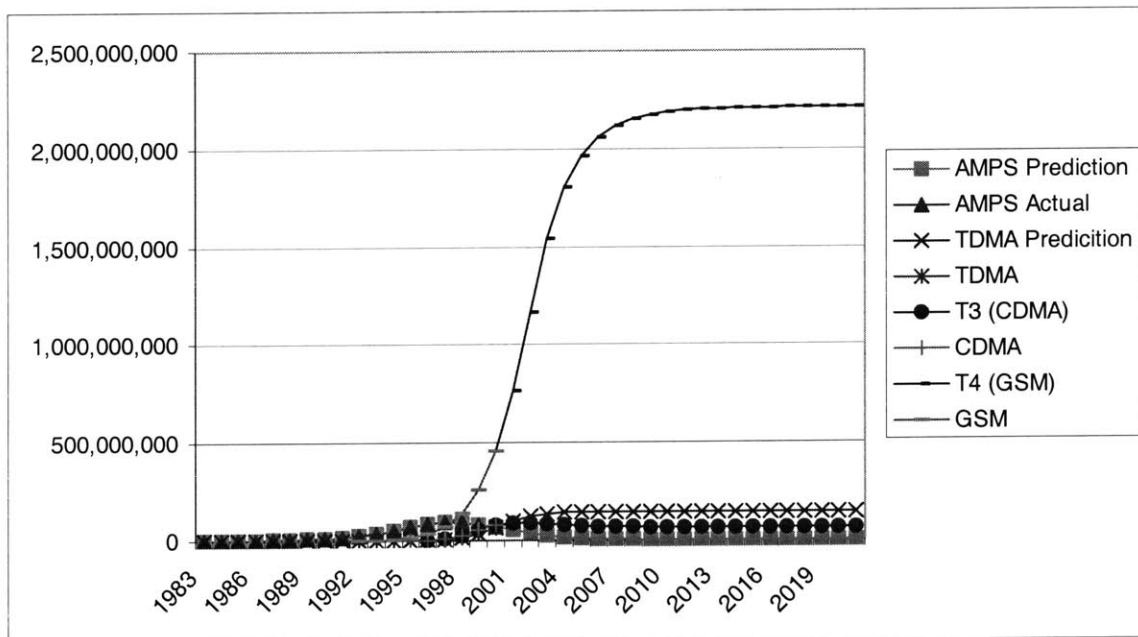


Figure 4-19. Worldwide 1G to 2G Model Prediction.

The model is based on a pure competition mode of technological interaction. The model predicts an eventual decay of 1G technologies and a S-curve growth of 2G technologies. The model predicts that GSM will maintain its world wide dominant position, and that TDMA and CDMA will maintain niche roles in the U. S. and other markets where they already have a dominant position. Special note should be given to the GSM result and it should be compared to the result for U. S. competition in figure 4-18. In the U. S. ignoring other subscribers worldwide, GSM doesn't look like it will survive. However, as 4-19 illustrates, GSM already has, and will maintain a worldwide dominant position.

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SECTION 5: SOFTWARE-DEFINED RADIOS

As highlighted in the previous sections, competing and often incompatible standards, modes, and frequencies now characterize wireless telecommunications services. Software-defined radio (SDR) is a rapidly evolving technology that promises an efficient method for the production of multimode, multiband, multifunctional wireless devices that can be enhanced using software upgrades. As its name implies, a software-defined radio system uses software to perform modulation/demodulation, functions traditionally implemented in hardware. The radio system can easily change to receive a different modulation scheme simply by using a different software routine to modulate and demodulate data onto the wireless carrier. This architecture offers several compelling advantages over hardware-based radio systems, which are traditionally built to receive a specific modulation scheme. However, the added complexity of the SDR technology needs to be weighted against the user need for such a technological innovation and potential competition for achieving the same capability more effectively.

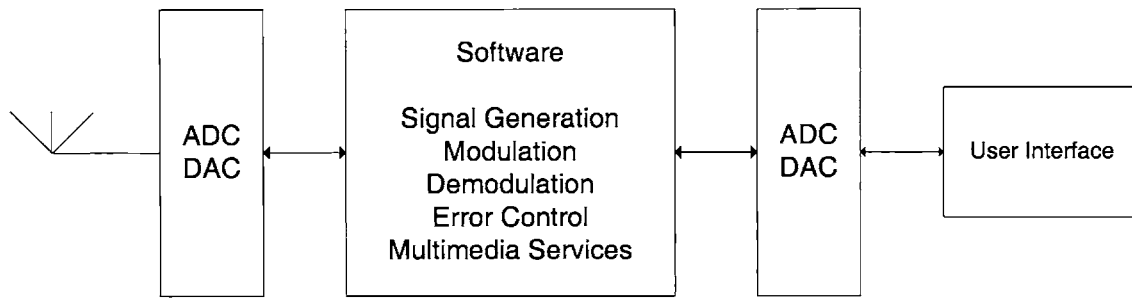
Overview

The common bond among all SDR technologies is the practical ability to reprogram, or configure, a particular radio function after the point of manufacture. A key technical challenge is to exploit this configurability to accommodate the tremendous growth in complexity and the wide variety of heterogeneous signal-processing functions required in advanced wireless communications-infrastructure equipment and user terminals. This challenge has set the stage for the emergence of a new class of heterogeneous, configurable, multiprocessing architectures that can bridge the gap between the energy efficiency required for broadband wireless solutions and the signal-processing flexibility required for SDR products. Following are some of the key technical elements and industry benefits of these new architectures.⁴⁵

The concept of software-defined radio originated with the military where it was originally used for electronic warfare applications. Now the cellular/wireless industries in the U.S. and Europe have begun work to adapt the technology to commercial communications services. SDR promises that future radio services will provide seamless access across cordless telephone, wireless local loop, PCS, mobile cellular and satellite modes of communication, including integrated data and paging. SDR enables flexible operation across a range of voice and data services, along with the ability to adapt to new voice and data services as they are developed and launched. As a result, SDR effectively addresses many of the challenging issues confronting the wireless industry. However, SDR is not a single technological breakthrough. It is a collection of implementation technologies that enable greater flexibility in a variety of mobile wireless products.

An ideal software radio transceiver is illustrated in Figure 5-1. Analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) at the transmit/receive antenna and handset allow all radio transmit, receive, generate signals, modulate/demodulate, and provide timing, control, coding and decoding functions to be performed in software. The software radio includes many non-digital signal processing (DSP) hardware components like RF conversion, RF distribution, anti-aliasing filters, power handling, etc. But the increased performance and continually dropping costs for the enabling technologies of ADC and DAC converters, high speed digital signal distribution, DSP chips and embedded computing are facilitating a shift toward software intensive approaches specially in large scale telecommunication systems applications.

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* ADC - Analog to Digital Converter
DAC - Digital to Analog Converter

Figure 5-1. An Idealized Software Radio

A block diagram of an idealized software defined radio is demonstrated. Analog-to-Digital Converters (ADCs) and Digital-to-Analog converters (DACs) at the transmit/receive antenna and handset allow all radio transmit, receive, generate signals, modulate/demodulate, and provide timing, control, coding and decoding functions to be performed in software.

The ideal software radio interoperates with any communications service in its RF preselector band and ADC bandwidth. By running a different algorithm, the software radio instantly reconfigures itself to the appropriate signal format. This opens interesting possibilities for expanded radio services. A future software radio might autonomously select the best transmission mode (Personal Communication Network, Mobile Cellular Network, etc.), send probing signals to establish a link, explore communications protocols with the remote end and adapt to the remote signal format. It could select the mode for lowest cost, service availability or best signal quality. The software radio then reconfigures itself on the fly to support the required services. This kind of flexibility opens opportunities for reduced costs and improved services for military as well as civilian applications. Prior generation military radios used single signal formats. In the past, communication centers required different radios for different modes: SINGCARS for voice, TACFIRE for data, etc.

As mobile communications networks evolve to accommodate accelerating demand for wireless voice and data services, equipment manufacturers and network operators are being forced to confront many difficult and simultaneous challenges. These challenges include supporting explosive subscriber growth using multiple standards, modes, and frequencies (see sections 3 and 4); stemming the proliferation of equipment and service platforms; and meeting the demand for wireless Internet and information services. Supporting the higher cost and longer lifetime of third-generation (3G) terminals, adapting to the growing pace of competition and consolidation, and overcoming the cost and scarcity of wireless spectrum are also prime concerns.

In light of these challenges, SDR offers the wireless industry an alternative vision, one where every consumer would have a personalized device capable of working anywhere, system operators would have future proof networks, and manufacturers could service a mass-customized market with one product platform. In addition, consumers would be able to download new services instantly to a single device, and network operators could achieve nationwide and global-network footprints independent of air interface.

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Software-Defined Radio Research

The DOD has devoted considerable attention to developing software-defined radios. The most prominent of these initiatives was the SPEAKeasy program sponsored by DARPA, the Air Force Rome Laboratory, and the Army Communication Electronics Command. SPEAKeasy was a Department of Defense and industry program initiated to develop a software-programmable radio operating between radio frequencies of 2 megahertz (MHz) to 2 gigahertz (GHz), employing waveforms selected from memory, downloaded from floppy disk, or reprogrammed over the air. This programmability allows a SPEAKeasy radio to become interoperable with whatever radio system it encounters. This becomes advantageous when it is not practical or cost effective to have as many radios as would be needed to communicate on every desired waveform or system. In phase 1 of the program, analog-to-digital (A/D) converters were used to complete the radio signal path and high-speed digital signal processors (DSPs) were used for filtering and demodulation. The key technologies demonstrated in phase 1 include digital frequency conversion and wideband signal processing.

SPEAKeasy was not only designed to implement a totally open architecture, offering interoperability and full programmability, but it offers secure communications as well—all combined into a compact configuration. Future capabilities can be easily incorporated by upgrading internal components with current state-of-the-art technology. In SPEAKeasy phase 2, modular radio elements (separate modules for the analog elements, A/D converter, and digital-signal processors (DSPs)) are integrated on an open-architecture bus. The key objective of phase 2 was to demonstrate a software-defined networking radio with support for legacy and future waveform evolution using a single architecture. This approach increased production volume, reduces costs, and enhances logistical support. The open-architecture design implies that competitive bids would be sought for commercial boards, modules, and software. Other goals include the use of commercial modules in the radio and the commercialization of any functions developed specifically for the radio. Originally designed for military applications to bridge the wireless gap of diverse tactical radio systems in use by different armed services, SPEAKeasy can also meet the diverse requirements of the global wireless industry. Among the SDR-driven contributions to this are the radio device applications programmer's interface (API) from SPEAKeasy (II). SPEAKeasy technology was eventually transitioned to the DoD Joint Tactical Radio System (JTRS) program.

The Naval Research Laboratory has an ongoing research program focusing on a software-defined radio known as the Joint C4I Terminal (JCIT). The JCIT grew out of an Army requirement for an advanced, helicopter-based command-and-control system. The JCIT will incorporate multiple software-defined radios for combat net, intelligence communications, and military data links on a single platform.

The advanced communications engine (ACE) evolved from a project sponsored by DARPA. The ACE is a software-defined digital radio with capabilities for multiple simultaneous band and channel transmissions (it has six receiving and transmitting channels). The initial prototypes demonstrate "dual-use" (i.e., both military and commercial) capabilities including those of combat net radios SINCGARS and Have Quick (a UHF system designed to provide secure air-to-air and air-to-ground communications with AJ capabilities), and commercial avionics radios such as GPS, VHF air to ground, and the aircraft communications addressing and reporting system.

A very ambitious program, Millennium, was initiated to design an ultra-wideband radio. One objective was to demonstrate extremely high-speed (approximately 1 billion samples per second) ADCs for both military and commercial communications. After the data conversion process, all tuning, filtering, demodulation, and decoding functions are performed by software.²³

Europeans have also had a series of SDR research programs, notable among these are the FIRST program. Flexible Integrated Radio Systems Technology (FIRST) was a European collaborative research project investigating the new technology of Intelligent Multimode Terminals (IMTs), and in doing so embraces the concept of software radio. The consortium brings together a wide range of expertise from the telecommunication and related industries, from network operators and base-station manufacturers to university research departments and high-tech R&D companies. The goal of the project was for the telecommunications industry to make a significant contribution to the adoption of IMTs and software radio technology, and thus it influenced the Universal Mobile Telecommunication System (UMTS) standard in Europe.

Cellular System Architecture⁴⁶:

Cellular communications refers to a sub-field of mobile communications in which the geographical area is sub-divided into cells. Each cell is handled by a cellular network entity called a Base Transceiver Station (BTS). End-user devices (such as cellular phones or vehicle-mounted phones) are called Mobile Stations (MS) and they talk to the BTS using an over-the-air radio interface. This is the only wireless interface in the cellular network, which means it is based on radio communication. Since radio frequency spectrum is at a premium, the aim is to pack as many MSs as possible in a single radio frequency band. Unlike other radio systems, in cellular communications the MS is constantly moving through different cells, as the end-user moves about. This transition from one cell to the other should be transparent to the end-user. To accomplish this, the MS and BTS perform something called hand-over. As the name suggests, this involves seamlessly handing over the MS from one BTS to another, when the user crosses a cell. Other key entities that are part of the cellular network include the Base Station Controller (BSC), which manages the radio channels and the hand-over between BTSs, the Mobile services Switching Center (MSC) which connects the cellular network to external networks such as the regular phone system, the Home Location Register (HLR) which contains information about the subscriber and the current location of the MS, and the Visitor Location Register (VLR) which contains dynamic information as well as copies of the HLR for MSs currently in the area.

Figure 5-2 shows the cellular network architecture in terms of components and interfaces. The different components are described below. Each major module and interfaces is described in the following.

Mobile Station (MS): A Mobile Station is usually the only equipment the end-user ever sees from the whole cellular system. Mobile Stations could be cell phones or vehicle mounted phones etc. Besides doing radio and processing functions to access the cellular network through the radio interface, a mobile station offers an interface to the human user (such as a microphone, display and keyboard) or some other terminal equipment (such as an interface to a PC or FAX machine in case of the MS being used as a modem).

Base Transceiver Station (BTS): The BTS is in contact with the MS over the radio interface and with the BSC using landline (usually a high speed T1/E1) interface. A BTS comprises radio transmission and reception devices and antennas. BTS can be considered as complex radio modems and have a few other functions, like helping BSC to perform hand-over, and sometimes

performs transcoding and rate adaptation etc. One or more MSs are connected to the BTS and the BTS is connected to a BSC.

Base Station Controller (BSC): BSC acts as management equipment for the radio interface. This is done through remote commands to the BTS and the MS. One BSC manages more than one BTS. The main responsibilities of the BSC include management of radio channels and hand-over management. BSC is connected to the MSC on the network side.

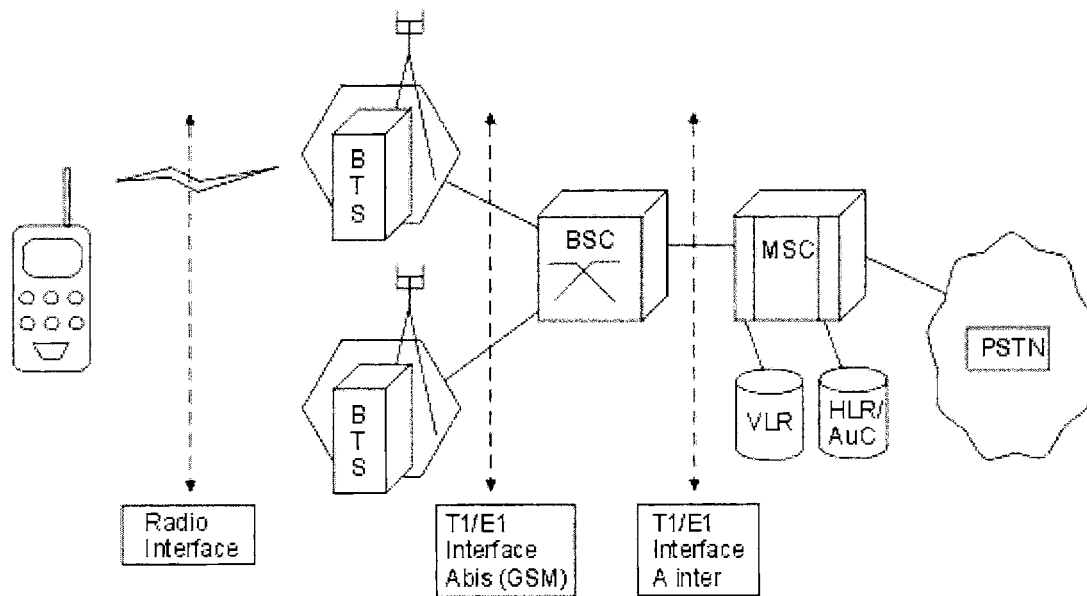


Figure 5-2. Cellular System Architectural Components⁴⁷

This figure shows the relationship between the handheld, radio interface, telecommunications infrastructure (T1/E1 Interface), and the mobile switching center (MSC) and the public switched telephone network (PSTN)

Mobile services Switching Center (MSC): The main function of MSC is to coordinate the setting up of calls to and from cellular users. The MSC has an interface to one or more BSCs on one side and with external networks on the other side. One node of this external network could be a Public Switch Telephone Network (PSTN, the regular land line telephone network). The Home Location Register (HLR) is usually considered a part of the MSC. It is a database of subscriber information relevant to the telecommunication services, independent of the actual location of the subscriber. HLR also includes some information related to the current location of the subscriber for incoming call routing purposes. A functional sub-division of the HLR includes the Authentication Center (AuC), the role of which is limited to the management of the security data for the authentication of subscribers.

Software Radio Architecture

The choice of architecture for a two-way wireless network involves numerous issues dealing with the most fundamental aspects of network design. The primary issue is whether to use a peer-to-peer or a base-station-oriented network configuration. In a peer-to-peer architecture, communication flows directly among the nodes in the network and the end-to-end process

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consists of one or more individual communication links. In a base-station-oriented architecture, communication flows from network nodes to a single central hub.

The choice of a peer-to-peer or base-station-oriented architecture depends on many factors. Peer-to-peer architectures have inherently more reconfigurability and do not necessarily have a single point of failure, enabling a more dynamic topology. The multiple hops in the typical end-to-end link offer the advantage of extended communication range, but if one of the nodes fails then the localized link path needs to be reestablished.

Base-station-oriented architectures tend to be more reliable because there is only one hop between the network node and central hub. In addition, this design tends to be more cost-efficient because centralized functions at the hub station can control access, routing, and resource allocation. Another problem with peer-to-peer architecture is the significant co-site interference that arises for multiple users in close proximity to each other—a problem that can be averted in a base-station-oriented architecture by the coordinated use of transmission frequencies or time slots. The wireless base-station-oriented architecture is exemplified by cellular telephone systems, whereas the most common peer-to-peer architecture for wireless systems is a multihop packet radio.

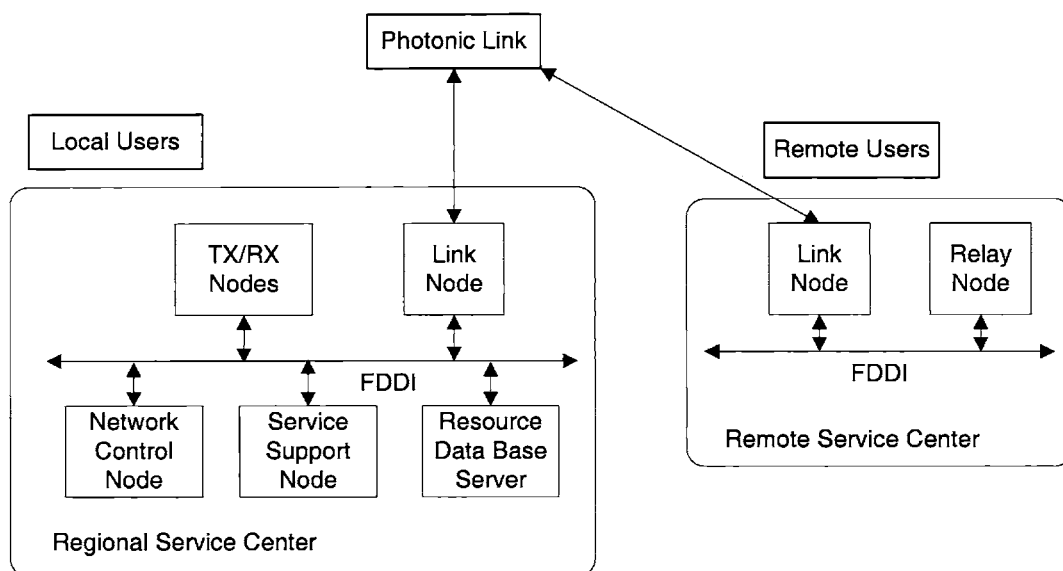


Figure 5-3. Telecommunication System Architecture⁴⁸

The data links, mobile radios and local area networks (LANs) illustrate the system architecture of a software radio oriented wide area telecommunications system. A regional service center provides central control while local service centers provide statistical multiplexing, bandwidth management and ancillary data.

The data links, mobile radios and LANs of figure 5-3 illustrate the system architecture of software radio oriented wide area telecommunication system. In Figure 5-3, a regional service center provides central control while local service centers provide statistical multiplexing, bandwidth management and ancillary data. These telecommunication systems have used message passing for distributed remote control since 1982. Layering and message passing have provided a robust, extensible application architecture through several generations of hardware and operating systems. Figure 5-4 demonstrates how telecommunication systems connectivity services are layered according to the International Standards Organization/ Open Systems Interconnect (ISO/OSI) model (a) within a service center, (b) on line of sight radio data links and (c) on wide

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area remote satellite links. With this approach 44 thousand lines of code (KLOC) allocated to connectivity layers (Connectivity Code) insulates over half a million lines of code for changes in the implementations (SDR Apps).⁴⁸

This KLOC metric, based on an early SDR implementation, illustrates the advantage of an abstracted layered architecture.⁴⁸ When changes are made to the any layer beside the application layer, only a small percentage of implementation code would have to be modified. The larger investment in applications would be preserved through numerous changes in the underlying implementation layers.

Software is already replacing hardware in the wireless-equipment manufacturing process. This move consolidates product platforms and increases their flexibility. Many manufacturers currently support some reprogramming of base-station functions and configurations in the field, albeit over proprietary-network interfaces. In handsets, on the other hand, this software is not yet widely designed to support reprogramming after the manufacturing process is complete. Driven by the growing needs of network operators to support more advanced management of deployed handsets (provisioning, repairs, upgrades, personalization, and multimode roaming), SDR capabilities will soon be expanded to support software download—including over-the-air downloads—and reconfiguration of user terminals.

In the long run, SDR also shows promise as a key technology, which, in conjunction with spectrum-management policies, can enable higher subscriber densities, more flexible service offerings, and more efficient use of available spectrum in wireless networks.

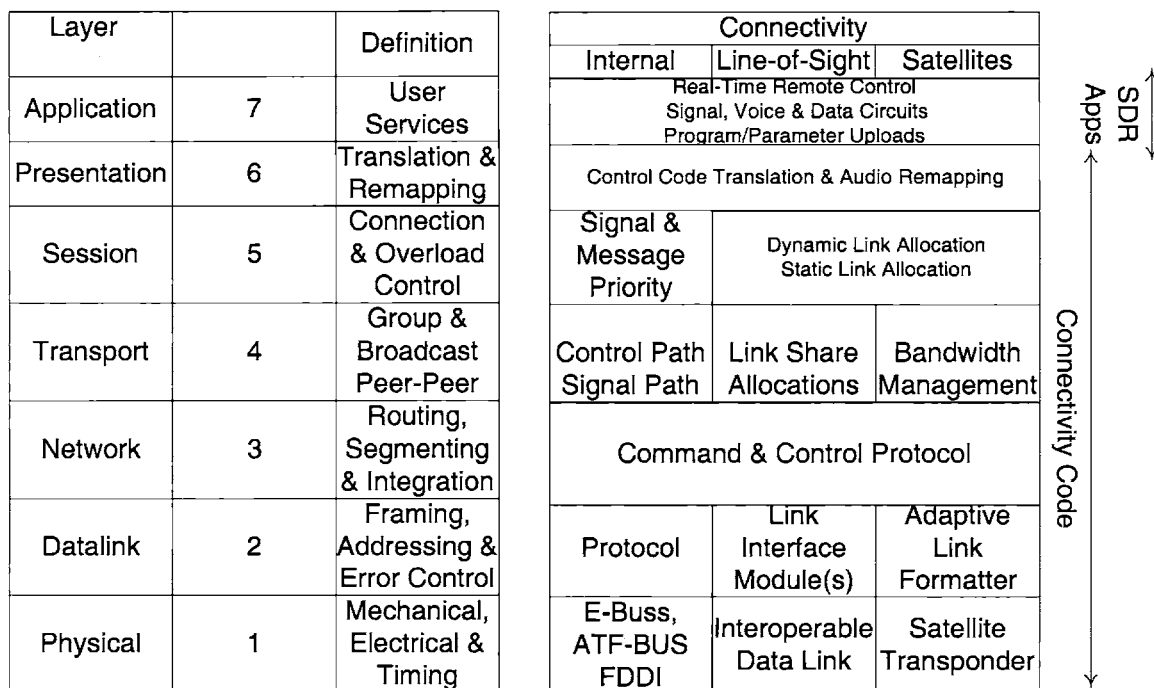


Figure 5-4. Layered Connectivity Architecture⁴⁸

This figure demonstrates how telecommunication systems connectivity services are layered according to the International Standards Organization/ Open Systems Interconnect (ISO/OSI) model (a) within a service center, (b) on line of sight radio data links and (c) on wide area remote satellite links. With this approach 44 thousand lines of code (KLOC) allocated to connectivity layers (Connectivity Code) insulates over half a million lines of code for changes in the implementations (SDR Apps).

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Radio architectures may be plotted in the phase space of network organization versus channel data rate as shown in figure 5-5. These architectures have evolved from early point-to-point and relatively chaotic peer networks (e.g. citizens band and push-to-talk mobile military radio networks) toward more hierarchical structures with improved service quality. In addition, channel data rates continue to increase through multiplexing and spectrum spreading. In a multiple hierarchy application, a single radio unit, typically a mobile terminal, participates in more than one network hierarchy. A software radio terminal, for example, could operate in a GSM network, an AMPS network, and a future W-CDMA network. The complexity of functions, components and design rules of these architectures continues to increase with each generation. At the same time, software radio architectures simplify hardware component tradeoffs and provide new ways of managing the complexity of emerging standards, through increases in software complexity.

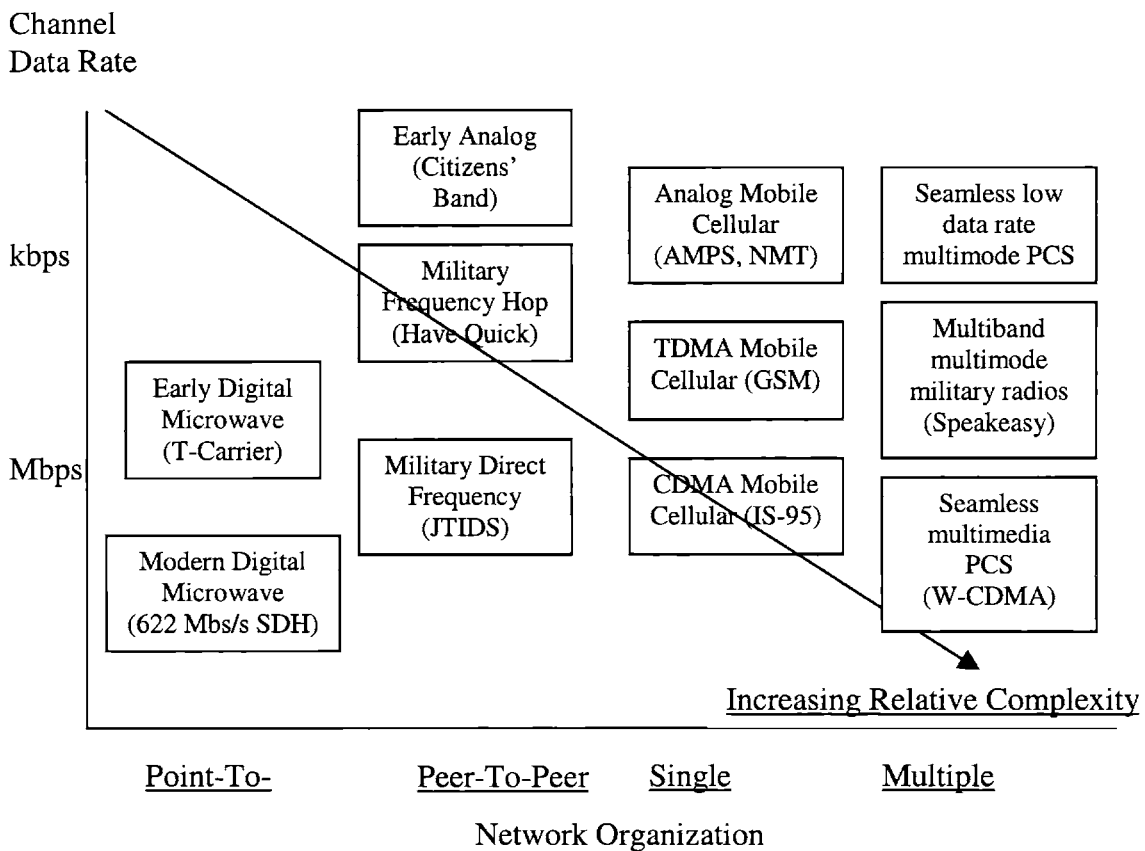


Figure 5-5. Radio Architectures Relative Complexity Evolution⁴⁹

This figure attempts to categorize the relative complexity of various radio system architectures according to relative architectural complexity and channel data rate. Those systems in the lower right hand corner of the curve are more difficult to implement in an SDR than those in the upper left corner.

First-generation hardware-based radio systems are built to receive a specific modulation scheme. A handset is built to work over a specific type of analog network or a specific type of digital network. The handset works on one network or the other, but not both, and certainly cannot cross between analog and digital domains.

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Second-generation radio systems are also hardware-based. Miniaturization enables two sets of components to be packaged into a single, compact handset. This enables the unit to operate in dual mode—for example, switching between AMPS or TDMA modulation as necessary. Such handsets are implemented using "snap-in" components; two existing chip-sets—one for AMPS and one for TDMA, for example—are used together. Building such handsets typically costs only 25 to 50 percent more than a single-mode handset, but offers network operators and users far more flexibility.

Handsets that work across four or more modes/bands entail far more complexity and processing power and call for a different architecture altogether. The architecture is based in software and programmable digital signal processors (DSP) and is SDR. It represents the third generation of radio systems. As new technologies are placed onto existing networks and wireless standards become more fragmented—particularly in the U.S.—the need for a single radio unit that can operate in different modes and bands becomes more urgent. A software radio handset could, for example, operate in a GSM-based PCS network, a legacy AMPS network, and a future 3G high speed digital network.

SDR also promises to support incremental service enhancements through a wide range of software tools. These tools assist in analyzing the radio environment, defining the required enhancements, prototyping incremental enhancements via software, testing the enhancements in the radio environment, and finally delivering the service enhancements via software and/or hardware.

Multimode/Multiband

As competing technologies for wireless networks emerged in the early 1990s, it became apparent that subscribers would have to make a choice. The newer digital technologies offered more advanced features, but coverage would be spotty for some years to come. The older analog technologies offered wider coverage, but did not support the advanced features. A compromise was offered in the form of wireless multimode/multiband systems that let subscribers have the best of both worlds. As referred to in subsequent section, this innovation is termed a gateway innovation in the management literature.

At the same time, wireless multimode/multiband systems allow operators to economically grow their networks to support new services where the demand is highest. With multimode/multiband handsets, subscribers can access new digital services, as they become available, while retaining the capability to communicate over existing analog networks. The wireless system gives users access to digital channels wherever digital service is available, while providing a transparent handoff when users roam between cells alternately served by various digital and analog technologies. As long as subscribers stay within cells served by advanced digital technologies, they will continue to enjoy the advantages provided by these technologies. When they reach a cell that is supported by analog technology, they will have access only to the features supported by that technology. The intelligent roaming capability of multimode/multiband systems automatically chooses the best system for the subscriber to use at any given time.

3G radio systems are agile in frequency and extend this flexibility even further by supporting more modes and bands. It is important to remember, however, that software radio systems may never catch up to encompass all the modes and bands that are available today and which may become available in the future. Users will always be confronted by choices. Making the right

choice will depend on calling patterns, the features associated with the different technologies and standards, and the type of systems in use at international locations visited most frequently.

Multimode and multiband handsets have been available from several manufacturers since 1995. These handsets support more than one technology for its mode of operation and more than one frequency band.

An example of a multimode wireless system is one that supports both Advanced Mobile Phone Standard (AMPS) and Narrowband AMPS. Narrowband AMPS is a system-overlay technology that offers enhanced digital-like features, such as Digital Messaging Service, to phones operating in a traditional analog-based AMPS network. Among the vendors offering dual-mode AMPS/N-AMPS handsets is Nokia, the world's second largest manufacturer of cellular phones. Another example of a multiband wireless system is one that supports both GSM at 900 MHz and GSM at 1800 MHz in Europe. Among the vendors offering dual-band GSM handsets is Motorola. The company's International 8800 Cellular Telephone allows GSM 1800 subscribers to roam on either their home or GSM 900 networks (where roaming agreements are in place), using a single cellular telephone. Handsets can also be both multimode and multiband. Ericsson, for example, offers dual-band/dual-mode handsets that support communication over both 800 MHz AMPS/TDMA and 1900 MHz TDMA networks. Subscribers on a TDMA 1900 channel can handoff both to/from a TDMA channel on 800 MHz as well as to/from an analog AMPS channel.

Multimode and multiband wireless systems allow operators to expand their networks to support new services where they are needed most, expanding to full coverage at a pace that makes economic sense. From the subscribers' perspective, multimode and multiband wireless systems allow them to take advantage of new digital services that are initially deployed in large cities, while still being able to communicate in areas served by the older analog technologies.

With its multimode capabilities, the wireless system preferentially selects a digital channel wherever digital service is available. If the subscriber roams out of the cell served by digital technology—from one served by CDMA to one served by AMPS, for example—a handoff occurs transparently. As long as subscribers stay within CDMA cells, they will continue to enjoy the advantages the technology provides, such as better voice quality and soft handoff, which virtually eliminates dropped calls. When subscribers reach a cell that supports only AMPS, voice quality diminishes and the chances for dropped calls increases.

However, these multimode/multiband handsets are not software-programmable. They rely instead on packaging multiple sets of hardware in the same handset. Miniaturization of the various components makes this both practical and economical, but this approach has its limitations when the number of modes and frequencies that must be supported goes beyond two or three. Beyond that point, a totally new approach is required that relies more on programmable components.

The software radio architecture is widely applicable to trunk radios, mobile military communications, and satellite mobile systems. In an advanced application, a software radio does not just transmit: it characterizes the available transmission channels, probes the propagation path, constructs an appropriate channel modulation, electronically steers its transmit beam in the right direction, selects the appropriate power level, and then transmits. A software radio does not just receive: it characterizes the energy distribution in the channel and in adjacent channels, recognizes the mode of the incoming transmission, adaptively nulls interferers, estimates the dynamic properties of the desired-signal multipath, coherently combines desired signal multipath, adaptively equalizes this ensemble, trellis decodes the channel modulation, and then corrects

residual errors via forward error correction (FEC) decoding to receive the signal with lowest possible bit-error rate.

SDR Standards

The wireless industry has experienced a recent flurry of standards and regulatory activities focused on SDR, driving home the urgency with which SDR solutions are being sought.

The Software-Defined Radio Forum (formerly the Modular Multifunction Information Transfer System, or MMITS Forum) is an industry consortium dedicated to open architecture Plug-and-Play digital and software radios. Created in March 1996 with an initial focus on SPEAKeasy, MMITS has grown to embrace civil and commercial markets with a global outreach including the U.S., Europe and Asian suppliers of software and digital radio technology. The debates in the SDR Forum have focused work on over the air downloads, highlighted in "Mode-Switching and Software Download for Software Defined Radio. The SDR Forum Approach."

The SDR Forum is dedicated to supporting the development, deployment, and use of open architectures for advanced wireless systems. To that end, the Forum helps to⁵⁰:

- Accelerate the proliferation of enabling software definable technologies necessary for the introduction of advanced devices and services for the wireless Internet
- Develop uniform requirements and standards for SDR technologies to extend capabilities of current and evolving wireless networks.

The SDR Forum is organized into several committees and working groups including a Regulatory Committee, a Markets Committee, and Technical Committee. The Regulatory Committee's charter is to promote the development of a global regulatory framework supporting software download and reconfiguration mechanisms and technologies for SDR-enabled equipment and services. The Markets Committee's charter is to raise industry awareness through public relations activities, including published articles, press releases and representation at industry trade shows; to increase and maintain Forum membership; and to collect and analyze market data on all industry segments. The Technical Committee's charter is to promote the advancement of software-defined radios by using focused working groups to develop open architecture specifications of hardware and software structures.

The Working Groups include a Download/Handheld group, a Base Station/Smart Antennas group, and a Mobile group. The Download/Handheld group's charter is to promote the use of software defined radio technology in handheld terminals, providing dynamic reconfiguration under severe constraints on size, weight, and power. The Base Station/Smart Antennas group's charter is to promote the use of software defined radio and reconfigurable adaptive processing technology in wireless base stations world-wide for terrestrial, satellite, mobile, and fixed services. The Mobile group's charter is to promote the use of software defined radio technology in commercial and military applications under adverse terminal conditions where station mobility, dynamic networking, and operational flexibility are required using a variety of wireless and network interfaces.

The SDR Forum Regulatory Committee helped coordinate activities leading to the FCC's issue of a Notice of Inquiry (NOI) on SDR in March 2000. As a result of the enthusiastic response to this NOI by major wireless equipment manufacturers and network operators, an initial FCC ruling was provided in the spring of 2001. This ruling removed regulatory hurdles to the further development and deployment of SDR equipment and systems by providing information on how

equipment would be certified by the FCC. The SDR Forum has also forged strategic partnerships with several industry standards committees such as UMTS and IMT that are developing the specifications for 3G wireless.

However, there is still debate within the industry as to what aspects of SDR to standardize. To the cellular handset manufacturer, the radio interface is perhaps the first thing that springs to mind. A global radio interface standard to act as a bearer for local over the air download or to provide switching instructions to handsets containing a set of preloaded options, a global beacon channel could be desirable. If software radio is to fulfill its full potential, it will be necessary to create open standard to allow different vendors' software to function on different hardware platforms, in turn connected to different networks, using different vendors' infrastructure. This is a non-trivial scenario.

SDR as a Product Platform

As mobile communications networks evolve to accommodate accelerating demand for wireless voice and data services, equipment manufacturers and network operators are being forced to confront many difficult and simultaneous challenges. These challenges include supporting explosive subscriber growth using multiple standards, modes, and frequencies; stemming the proliferation of equipment and service platforms; and meeting the demand for wireless Internet and information services. Supporting the higher cost and longer lifetime of third-generation (3G) terminals, adapting to the growing pace of competition and consolidation, and overcoming the cost and scarcity of wireless spectrum are also prime concerns. In the face of these challenges, SDR offers the wireless industry an alternative vision, one where every consumer would have a personalized device capable of working anywhere, system operators would have future proof networks, and manufacturers could service a mass-customized market with one product platform. In addition, consumers would be able to download new services instantly to a single device, and network operators could achieve nationwide and global-network footprints independent of air interface.

Software is already replacing hardware in the wireless-equipment manufacturing process. This move consolidates product platforms and increases their flexibility. Many manufacturers currently support some reprogramming of base-station functions and configurations in the field, albeit over proprietary-network interfaces. In handsets, on the other hand, this software is not yet widely designed to support reprogramming after the manufacturing process is complete. Driven by the growing needs of network operators to support more advanced management of deployed handsets (provisioning, repairs, upgrades, personalization, and multimode roaming), SDR capabilities will soon be expanded to support software download—including over-the-air downloads—and reconfiguration of user terminals.

The software programmable features of an SDR can be used as a form of mass customization. Creation of a base product with a minimum of features and then adding modes, bands, applications and features as the market evolves may be an effective way to bring a new SDR-based handset into the market. When managing the evolution of such a product family the market applications of the technology must be considered including derivative products made for various customer groups; the company's product platforms; the common technical and organizational building blocks that are the basis of these product platforms.

The software programmability can also provide customer insights. Customer insights are a foundation of product platforms, and intimate knowledge of customer needs is every bit as important as breakthrough technology. This discovery of latent needs may be available through the iterative application and air-interface development enabled through SDR technologies.

However, a company must examine its product architecture carefully to identify those particular subsystems that have the potential of unique proprietary technology and production, i.e., to not be at parity with the rest of the world. Such key subsystems can drive the entire portfolio and should therefore be standardized across it. This type of standardization is an internal form based on proprietary high-value-added technology. In this concept, the platform is developing add-in modules that can be seamlessly plugged into the engine creates the engine and derivative products. SDR has the potential to disrupt the value with such a strategy. If the entire handset becomes an open software programmable platform, others may be able to appropriate part of the value chain by writing software to run on the SDR platform.

However, economies of scale can also benefit the developer. Larger markets can be addressed with the same basic set of software. A software developer can provide a family of products without starting from ground zero to create every single one.

SDR Enabling Technology

There are three essential elements to SDR. Each continues to be aggressively developed by commercial wireless hardware and software manufacturers around the world. The first element, and the one most commonly associated with SDR, is the ability to consolidate product platforms by supporting cellular and non-cellular multiple and simultaneous modes and bands. This capability has traditionally been realized using a design approach that balances performance and flexibility through a combination of software, using a programmable digital signal processor (DSP) and hardware using application-specific integrated circuits (ASICs). Unfortunately, with signal-processing requirements of advanced wireless air-interface standards increasing at a rate faster than the performance of available processors, this balance has become difficult to maintain. As a result, manufacturers are now being forced to examine alternative signal-processing architectures.

The other SDR elements are a flexible applications-development environment and the ability to support secure and efficient software downloads, as well as constraints on the selection of an appropriate signal-processing architecture. The relative superiority of a particular SDR product architecture depends on parameters, such as product cost, product size, power dissipation, design re-use, ease of software development and maintenance, and efficiency of software download and reconfiguration. In addition, the evolution of wireless networks from narrowband (voice) to wideband (voice and data) has triggered a massive increase in the complexity of the underlying signal processing algorithms.

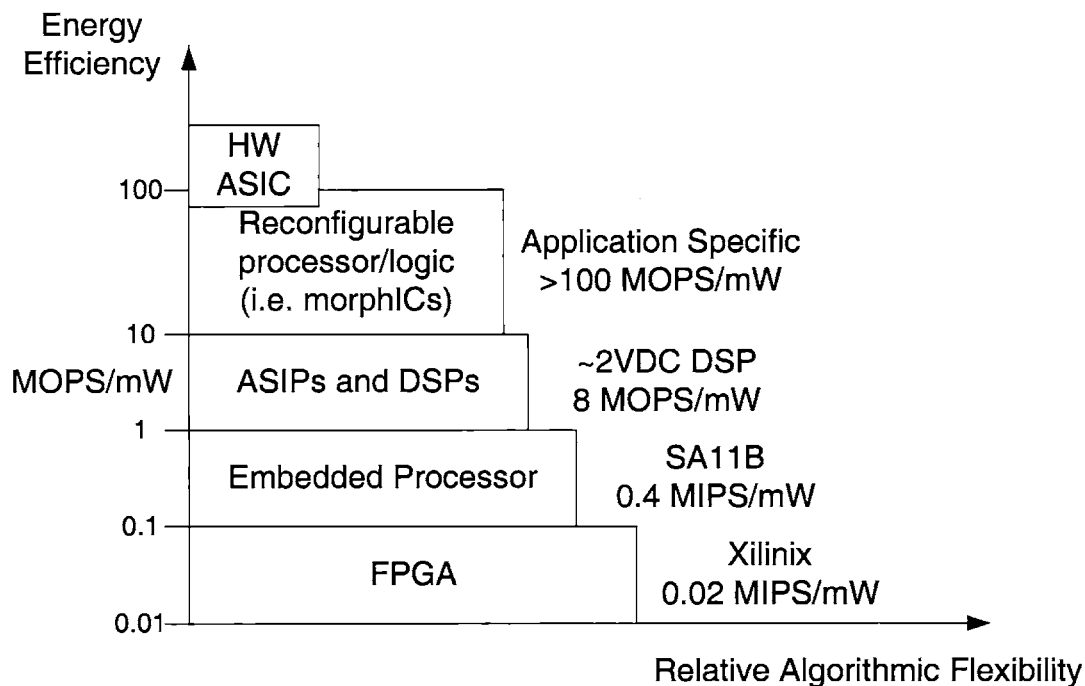
The signal-processing “horsepower” necessary to support continuing advancements in digital air interfaces has grown from tens of millions of instructions per second (MIPS) for second-generation (2G) time-division multiple-access (TDMA) systems, to hundreds of MIPS for 2.5G TDMA and code division-multiple-access (CDMA) systems. For 3G wideband CDMA (WCDMA) systems, that number has risen to thousands of MIPS. In the case of WCDMA technology, data rates range from 64 kb/s to 2 Mb/s, with significantly greater algorithmic complexity in order to support higher data rates, higher subscriber densities, and a host of

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advanced network and service capabilities. Estimates for the computation requirements for WCDMA go as high as 1600 MIPS.⁵¹

Examining the various signal-processing alternatives that can be used to implement SDR product architectures for wireless base stations and handsets, a problem quickly becomes apparent. A large gap exists between dedicated hardware and programmable DSPs in terms of their computational efficiency with respect to power (millions of operations per second per milliwatt, or Mops/mW). As shown in Figure 5-6, ASICs can typically deliver 100 to 1000 Mops/mW, albeit with little flexibility, whereas even the latest programmable DSPs only now reaching the market deliver less than 10 Mops/mW.⁴⁵

Software has to be efficient in use of computational resources. A WCDMA despreader is the critical modem component for 3G. Since on the order of 100 operations may be required on the average to process a CDMA chip, a simple despreader would require on the order of 400 MIPS of processing capacity. Although DSP chips can deliver from 400 to 1000 MFLOPS, the trade-off of flexibility versus power dissipation generally favors an ASIC despreader. Software defined despreaders, however, could encapsulate ASIC personalities as downloadable objects for FPGAs.



Note: morphICs is proprietary reconfigurable logic architecture from Morpics, Inc.

Figure 5-6. Energy Efficiency of Various Digital Processing Technologies⁴⁵

To determine the technical feasibility of software defined radios, the key digital processing technologies must be considered. This figure demonstrates that various technologies have better performance for hand-held application. For handset application, a key metric is the battery life. However, as this figure demonstrates, there is a trade-off between energy efficiency and flexibility. Therefore, to gain the necessary processing flexibility for SDR implementation, energy efficiency must be sacrificed.

As more functionality moves from the DSP to a hardware-oriented implementation (ASIC) as a way to improve computational efficiency and reduce power consumption, a tremendous penalty is

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paid in terms of lost flexibility, as well as scalability, in the resulting hardware solution. With many changes still to come in terms of the algorithms and optimizations used in base stations and handsets to improve coverage, radio-link performance, capacity, over-the-network management, and the need to trade-off energy efficiency against flexibility becomes imperative. This need creates a signal-processing dilemma for equipment manufacturers already faced with critical time-to-market constraints.

Signal Digitization

Extensive development of analog-to-digital converters (ADCs) capability in recent years by the semiconductor industry has been stimulated by the prospects of digital wireless applications. This has resulted in improvements in accuracy, linearity, sampling rates, and resolution. There is still a trade-off between ADC performance and sampling rate that continues to be a limitation. ADCs performance trajectory is tied to that of semiconductor processing in general. With improvements expected in line with Moore's Law.

Semiconductor Functionality, Size, and Power Consumption (Moore's Law)

Silicon geometries continue to shrink, with circuit complexities still doubling every 18 to 24 months. This phenomenon has been termed "Moore's Law"^{52,53} by Intel's Gordon Moore. 0.18 and 0.13 micron silicon integrated circuit geometry is available today commercially, with significantly smaller geometries expected over the next 10 years. Smaller geometries result in an increase in the energy efficiency of ASICs and reconfigurable digital processors. Additionally, increased system functionality can be integrated monolithically onto the same integrated circuit. Supply voltages continue to decrease, with experimental digital signal processors running with voltages as little as 1 volt. Lowering the supply voltage corresponds to a reduction in power requirements, promising high performance digital signal processors in battery-powered devices.

DSP Power

DSPs are needed in SDR for digital transceiver functions such as equalization, Viterbi multichannel demodulation and correlation. Advances in DSP processors have included new architectural concepts and increasingly customized hardware engines, and new non-Von-Neumann architectures offer increasing power efficient implementation. Low-power consumption single chip DSPs with 1 GIPS at around 0.5W (2 MOPS/mW) power consumption have been spurred by 3G developments. Reconfigurable computing architectures, such as MorphICs, promise higher performance than generic DSPs with energy efficiency close to that of custom hardware based ASICs.

Hand-held Operating Systems and Software

There are numerous competing standards for the wireless device operating systems. The operating system allows applications to be portable. Isolating the link layer and hardware implementation from the higher valued applications. Operating systems sit between the application layer (layer 7) and the session layer (layer 5), see the OSI layer architecture in figure 5-4. There are several competing standards including BREW, Linux, PalmOS, and Symbian. Software is typically written in a high-level programming language. Sun Microsystems's PersonalJava specification, and Java 2 Platform, Micro Edition (J2ME) framework are an attempt to create a software environment that independent of the underlying operating system, and thus, even further abstracted from the underlying hardware.

All of these operating systems can be viewed as both complementary and competitors to SDR technology. Complementary in the aspect that the applications can become portable increasing their utility to run on multiple platforms. SDR functionality and modes can be embedded in applications that run and are managed by the respective operating system. Competitors in the aspect that it is the application that the user interacts with. Users care more about the applications than the underlying technology enabling it. Therefore, these operating systems and associated applications could be used on SDR phones as well as traditional hardware-based multimode/multiband handsets. In fact, the same applications could run on both types of handset depending on the needs of the user. To date, these operating systems are run exclusively and are planned for traditional hardware-based handsets.

PersonalJava, J2ME

The concept of the Virtual Machine, enabling Java programs to run on any processing platform, has created the “write once, run anywhere software paradigm. Once a Java program is running, new software components can be imported and dynamically incorporated, allowing functionality enhancement on the fly. Java is playing a significant role in the evolution of software, not least for mobile phones. PersonalJava is Sun’s version of a real-time environment for portable platforms. Traditionally, software applications have been written for specific phone models, although Sun Microsystems recently announced a software product called J2ME that also enables applications to be written for multiple mobile devices.

QUALCOMM's BREW

With 250 million CDMA phone users projected by 2004, QUALCOMM's BREW operating system is an attempt to tap into a huge market opportunity. More importantly, if successful, BREW could lead to the creation of an altogether new market for wirelessly downloaded software. QUALCOMM enjoys a significant advantage as a major chipset manufacturer. The BREW software will be shipped on top of QUALCOMM's CDMA chips, which will give developers an assurance that their software will be available to a significant number of consumers. That said, the growth of this market largely depends on the faster data speeds promised by 3G networks.

Qualcomm and Korean Telecom Freetel (KTF), announced on 24 October 2001 at the PT/Wireless & Networks Comm Beijing 2001 conference that the companies have reached an agreement for the commercial launch of KTFreeTel's applications service based on Qualcomm's BREW platform. KTF expects to roll out its BREW-enabled 'magic n' multipack service to subscribers on their cdma2000 1x network starting on 1 November 2001. KTF will be the first carrier in the world to launch the BREW platform services. (Source PR Qualcomm, 24 Oct 2001).

KTF conducted a successful public user trial of the BREW-enabled 'magic n' multipack service with 5,000 users in September and October 2001. The BREW-enabled service allows KTF subscribers to easily download and install a variety of applications in a matter of seconds. For KTF's customers, this means that the same BREW-enabled handset hardware can provide very different capabilities tailored to individual interests as subscribers download the applications they want from various categories, such as games and entertainment, business applications, messaging and navigation services. More than 160 applications are currently available from more than 20

companies, including Anicom, Gaeasoft, GeoTel and Lycos-Javagame.

Symbian

Symbian owns, develops and licenses a software platform for next generation mobile phones. Owned by Ericsson, Matsushita (Panasonic), Motorola, Nokia and Psion, Symbian's mission is to license the Symbian platform to all mobile phone manufacturers and to create a mass market for next generation mobile phones by working closely with wireless networks, content, messaging and enterprise wide solution providers. Symbian has developed a fully integrated operating system platform for GPRS-enabled Smartphones and Communicators⁵⁴. The platform also incorporates support for WAP, and advanced Bluetooth, providing all the building blocks necessary to create services and applications for wireless devices running on GPRS enabled networks.

The Symbian 2.5G platform is promoted as an open standard offering a robust, reliable platform for devices to attract third-party applications, content and services. Symbian's Java implementation runs within the Java 2 Platform, Micro Edition (J2ME) framework and includes all mandatory and most optional features defined in the PersonalJava Application Environment 1.1 specification. Symbian has also demonstrated its own reference design for Smartphones, complementing the many user interface designs that are already in development by licensees for Smartphones to address the mass consumer market of next generation mobile phones.

Symbian received a welcome boost on the 4th May 2001, when Nokia CEO Jorma Ollila announced that, by 2004, half of all Nokia's devices shipped will contain Symbian's operating system EPOC. Nokia stated that their announcement was made in order to satisfy software developers as to the number of future handsets that are likely to contain EPOC and to demonstrate that it is serious about Symbian.

Summary of all announced Symbian EPOC-based terminals are displayed in table 5-1.

Linux

Linux is an open source operating system that has application to the desktop computer and the mobile device. Several manufacturers have announced support for Linux in their mobile devices. Texas Instruments announced that its OMAP wireless architecture will support the Linux operating system. This effort extends the reach of the OMAP platform into the open source community to deliver embedded solutions for 2.5 and 3G mobile devices. Leading manufacturers including Nokia, Ericsson, Sony, Sendo, HTC and several others have selected the OMAP platform for their next generation wireless handsets and advanced mobile Internet devices.⁵⁵ Additionally, Galleo's Communicator model runs on the Linux operating system on GSM-9/18 and GPRS networks.

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Manufacturer	Model	Technology	Messaging	Microbrowser	Data Protocol	Data Rate	WAP
<u>Ericsson</u>	Communicator	GSM-9/18		Microbrowser	HSCSD		WAP
					GPRS		
<u>Ericsson</u>	R380e	GSM-9/18	SMS	WAP 1.2.1 Browser			WAP
<u>Ericsson</u>	R380s	GSM-9/18	SMS	Microbrowser			WAP
<u>Nokia</u>	7650	GSM-9/18	SMS	WAP 1.2.1 Browser	HSCSD	43.2 kbps	WAP
			MMS		GPRS		
<u>Nokia</u>	9210	GSM-9/18	SMS	Microbrowser	HSCSD	43.2 kbps	WAP
<u>Nokia</u>	9290	GSM-1900	SMS	Microbrowser			WAP

Table 5-1. Listing of Announced Symbian EPOC Terminals²⁹

This table lists the currently available handsets that run the Symbian operating system, and associated applications.

PalmOS

The PalmOS, the operating system in Palm Pilots and Handspring personal data assistants (PDAs) is also a contender of the wireless handheld market. Palm enabled phones can run all the applications available for the Palm platform. A big advantage over many of its contenders. Kyocera's QCP-6035 is a Palm enabled phone and PDA operating over CDMA-8/19 networks. Samsung's SPH-1300 has similar functionality to the Kyocera model, but operates over CDMA-19 networks.

Microsoft Stinger OS and Windows CE

Microsoft is delivering software to handset manufacturers and mobile operators for two phone solutions. Microsoft Mobile Explorer technology provides a lightweight microbrowser-based solution for mobile phones offering connected services. The Microsoft smart phone software platform, code-named "Stinger," is based on Microsoft Windows CE 3.0, a highly componentized embedded operating system for 32-bit connected client devices that demand rich applications and Internet services, and is specifically optimized for mobile phones to extend battery life and reduce memory requirements. Closely tying hardware advancements with software that takes advantage of the .NET platform, "Stinger" combines many personal information management services normally associated with PDAs with voice recognition technology to provide users with an intelligent communication experience.

High Tech Computer Corp. (HTC) and Microsoft Corp. announced they have agreed to design and develop next-generation phones based on the Microsoft Stinger smart phone software platform. (Source Press Release HTC, March 20, 2001). Sendo's model Z100 is

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a GSM triband phone enabled by the Stinger platform supporting GPRS. Other Windows CE based handhelds are listed in table 5-2.

Manufacturer	Model	Technology	Messaging	Microbrowser	Data Protocol	Data Rate	WAP
<u>Sewon</u>	Strata 5000	CDMA-800					
<u>LGIC</u>	HPC II	GSM-900					
<u>Mitsubishi</u>	Trium Mondo	GSM-9/18	SMS	Microsoft Pocket Explorer	GPRS	14.4 kbps	WAP
<u>Sagem</u>	WA 3050	GSM-9/18	SMS	Microsoft Pocket Explorer			WAP
<u>Sagem</u>	WA 3050 GPRS	GSM-9/18	SMS	Microsoft Pocket Explorer	GPRS		WAP

Table 5-2. Listing of Windows CE Based Handheld Phones.²⁹

This table lists the currently available handsets that run the Microsoft Windows CE based operating system, and associated applications.

Nokia GEOS

Table 5-3 demonstrated the Nokia models enabled by its GEOS operating system. This operating system is sponsored by Nokia and provides standard PDA functionality. It seems to be competing with the Nokia sponsored Symbian operating system.

Manufacturer	Model	Technology	Messaging	Microbrowser	Data Protocol	Data Rate	WAP
<u>Nokia</u>	9000il	GSM-1900					
<u>Nokia</u>	9110	GSM-900	SMS	Microbrowser			
<u>Nokia</u>	9110i	GSM-900	SMS	Microbrowser			WAP

Table 5-3. Listing of Nokia GEOS Based Handheld Phones.²⁹

This table lists the currently available handsets that run the Nokia GEOS based operating system, and associated applications.

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SDR Summary

Software radio architectures not only promise to reduce the complexity and expense of serving a diverse customer base, but they also promise to simplify the integration and management of rapidly emerging standards. With software-based radio systems, access points, cell sites, and wireless data network hubs can be reprogrammed to meet changing standards requirements rather than replacing them or maintaining them in parallel with a newer infrastructure.

From the perspective of users, the same hardware (handset) would continue to be used—only the software gets upgraded. This could signal the end of outdated cellular telephones. Consumers will be able to upgrade their phones with new applications—much like purchasing new programs to add new capabilities to their computers. Although the benefits are clear, commercial software-defined radio systems are still a few years away. Until they become available, users will have to make do with the current generation of multimode/multiband handsets.⁵⁶

Thanks to Moore's Law⁵², the size, weight, and power needed for gigafloating point operations per second (GFLOPS) processing capacities in affordable formats have yielded high-performance digital signal processors (DSPs) and application-specific integrated circuits (ASICs) embedded in cell phones and base stations. However, this also means that the ability to integrate increasing functionality into hardware becomes more feasible as more processing power is available on any discrete ASIC.

This section focused primarily on the technical specifications, feasibility, and some competitors to SDR handset technology. However, the success of a new technology is determined as much by the industry value-chain and market-needs as its technical feasibility. Technically, SDR promises to be the ultimate multiband/multimode handset, enabling portable applications and new air interfaces through dynamic software download. The need for such a technology is dubious, however.

First, as discussed in section 4, the wireless industry historical mode of technical standard interaction has been primarily pure competition. After a period of transition, the networks in the past have tipped to a finite set of standards, and the same is likely to happen with 3G rollout. This ultimately limits the need for a system that can operate over numerous competing standards to a very short time scale – at a cost that might not be acceptable to most users.

Second as will be discussed in section 6, the number of current handset models with more than two bands or modes is much smaller than those with even a single band, indicating that the market needs may be satisfied primarily by the simpler technology.

Finally, as will be discussed in section 7, the need for a gateway innovation to bridge incompatible networks is usually transitory and these innovations typically have a finite lifetime. Once a network obtains a critical mass such that it tips to a new standard, the gateway innovation is no longer needed and users are less likely to pay for the added complexity for marginal benefit.

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SECTION 6: CELLULAR HANDSET DOMINANT DESIGN

Then characteristics of the current cellular communications system handsets models are discussed, and a discussion of whether a dominant design has emerged in the cellular handset industry is undertaken. The features of current handsets provide an indication of design aspects important to cellular handset users.

Dominant Design in Wireless Handsets

To evaluate whether a dominant design has emerged in the wireless handset industry, several aspects of the product could be evaluated including: operating modes, features, display technology, flexibility, talk & standby times, weight, volume, degree of integration/modularity, and upgradeability. Unfortunately, much of the data in the cellular industry is proprietary, and difficult to obtain. In the following, discussion of the major features of dual-band CDMA 8/19 phones currently in the market are used as a case study. This is a manageable subset of all the phones currently in the market.

Table 6-1 demonstrates the number of cellular handset models that correspond to single or multiple band capability. This table is based on all the current handsets in the market or announced. For example, the first line “AMPS”, has 13 models. This means there are 13 handsets on the market with AMPS only capability. There is one handset with AMPS and CDPS capability.

The dual band GSM-8/19 has the most models available, and the most companies producing handsets for this market. This corresponds the most popular GSM bands in Europe and elsewhere. Note, as indicated in section 3, GSM has approximately 75% of the worldwide subscriber base with over 450 million subscribers. The so-called “World Phone” or GSM Triband, has approximately 67 models in the market. Also, single band phones such as the GSM-1800 (PCS) band in North America, have fewer models with GSM-1800 at 8 models, and GSM-1900 with 32. Also, the phones with backward compatibility to the 1G AMPS network (GSM-900/AMPS) have only 2 models in the market, primarily for the North American market where GSM networks only cover major metropolitan areas.

CDMA is represented by CDMA/J-TACS, CDMA-1700, CDMA-1900, CDMA-8/19, and CDMA-800. CDMA-800 has by far the most models (157) available of the CDMA standards, and also has the most subscribers worldwide. The single band CDMA-1900 follows this. The dual-band CDMA-8/19 has 51 models available. It should be noted that many of these CDMA models also include 1G (AMPS) compatibility.

The US TDMA standards for both single band and dual band phones have significantly less total models than either GSM or CDMA. Perhaps this isn’t surprising, since TDMA has less market share (and subscriber base) than either GSM or CDMA (see section 3). The dual band TDMA-8/19 has 48 models in market while TDMA-800 has 24 models. Note that many of these TDMA phones also have AMPS capability due provide coverage in rural areas where TDMA coverage is spotty.

Finally, in addition to AMPS, many of the old 1G networks throughout the world still have handsets available. NAMPS-800, NMT-400, NMT-900, and TACS all have a few handsets

available. These are mostly to serve the markets where 2G service is not yet available, or as a second phone to provide coverage in rural areas.

Table 6-2 is a demonstration of major features of all CDMA-8/19 handsets currently in the market. CDMA-8/19 was chosen for several reasons. These phones support dual bands, and in several cases, multiple modes. The number of models were not overwhelming to get data about, and they seem to capture the features being provided in other handsets both single and dual band. The phones have a wide array of features, both common and uncommon. A few of the phones have an operating system (Palm). 48% of the dual-band handset models include 1G (AMPS) capability, making them dual-band/dual-mode. Many of the phones have WAP capability (63%) and an Internet browser (79%). Most models support SMS (79%), Fax (50%), and data (73%). 23% also have an internal modem for interfacing to an external computer or PDA. Less handsets support EMS (4%). Of particular interest, 23% of all handsets on the market either support the 3G CDMA2000 protocol, or will support it through a software upgrade.

Although there is a proliferation of features, the current basic phone has fewer extra features. The basic contemporary handset includes at least one air-interface, a portable power source (NiCd or Li-Ion battery), a keypad for dialing and controlling the phone, a display to display numbers and messages, all packaged in a plastic case. These basic handsets do not have web browsers or other data capability. All handsets have these features as a minimum.

Modes	Models	Manufacturers
AMPS	13	Nokia, Sierra Wireless, CSI, Kyocera, Motorola, Telular, Ascom
AMPS/CDPS	1	PCSI
CDMA/J-TACS	5	Denso, Fujitsu, Kyocera, Panasonic, Toshiba
CDMA-1700	13	Hyundai, Hanwha, LGIC, Samsung
CDMA-1900	85	Nokia, Kyocera, Sierra Wireless, Wide Telecom, Acer, Denso, Fujitsu, Hyundai, Denso, LGIC, Nixxo, Haitai, Telular, Maxon, Samsung, Motorola
CDMA-8/19	61	Nokia, Sierra, Hyundai, Toshiba, Hanwha, Kyocera, Sewon, GTRAN, Fujitsu, LGIC, Nixxo, Telular, Air Prime, Samsung, Sanyo, Motorola, Sewon, Ericsson
CDMA-800	157	Nokia, Motorola, Ericsson, Wide, Hyundai, Toshiba, Acer, Solomon, Sewon, Sanyo, Hitachi, Casio, Sony, Kyocera, Panasonic, Denso, NEC, Fujitsu, Hanwha, Yiso, GTRAN, LGIC, Wide, Nixxo, Maxon, Samsung, Telson, Chinese manufacturers
GSM Triband	67	Motorola, Sierra, Hyundai, Option, Ericsson, Siemens, Trinity, Solomon, Sendo
GSM-1800	8	Motorola, Siemens, Telular, Nokia
GSM-1900	32	Nokia, Ericsson, Telespree, Hyundai, Philips, Mitsubishi, Motorola, Novatel
GSM-900/AMPS	2	Nokia, Ericsson
GSM-8/19	406	Ericsson, Motorola, Siemens, Teling, Nokia, NEC, DBTEL, Sendo, One-Comm, Motorola, GVC, Acer, Arima, Philips, Siemens, Chinese, Sony, Acer, Solomon, Xircom, Sendo, NEC, One-comBenefon, Siemens, Bodycom, Panasonic, Quanta, Telit, Alcatel, Sagem, Kyocera, LGIC, Sagem, Spectronic, Maxon, Nixxo, Sewon, Solomon, Voxson, Mitsubishi, Philips
GSM-900	66	Aselsan, Nokia, Alcatel, Siemens, DBTEL, Talk, Chinese, Motorola, Acer, Blaupunkt, LGIC, Benefon, Kyocera, Mondial, Maxon, Alcatel, Sagem, Ascom, Landis & Gyr, DBTEL, Voxson,
NAMPS-800	2	Motorola
NMT-450	5	Nokia, Benefon
NMT-900	1	Nokia
PDC-1500	39	Mitsubishi, Denso, Kenwood, NEC, Nokia, Panasonic, Pioneer, Sanyo, Sharp, Thoshiba, NEC, Panasonic, Kyocera
PDC-800	102	Kyocera, Sanyo, Mitsubishi, Ericsson, Fujitsu, Kokusai, Mitsubishi, NEC, Nokia, Panasonic, Sony
PHS	28	Kyocera, Toshiba, Panasonic, Sharp, Mitsubishi, Bandai, NEC, Panasonic, Sanyo, Kokusai
PHS/PDC-800	7	NEC, Panasonic, Sharp
TACS	3	Nokia, Voxson, Telular
US TDMA-8/19	48	Nokia, Ericsson, Mitsubishi, Telenion, CSI, NEC, Panasonic, Motorola, Telular, Maxon, Mitsubishi
US TDMA-800	24	Motorola, Telular, Samsung, Ericsson
W-CDMA	3	NEC, Panasonic

Table 6-1. Number of Handsets in Market for Various Air-Interface Standards as of December 2001²⁹

This table lists the number of handsets available for various standards and modes as of December 2001. For example, GSM-8/19 (GSM system support with dual band of 800 MHz and 1900 MHz) has the most models of handsets available with 406 units.

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<i>Model</i>	<i>Manufacturer</i>	<i>Introductory Date</i>	<i>Operating System</i>	<i>IG</i>	<i>WAP</i>	<i>Browser</i>	<i>Bluetooth</i>	<i>SMS</i>	<i>EMS</i>	<i>Fax</i>	<i>Data</i>	<i>CDMA 2000 Suppt</i>	<i>Modem</i>	<i>Comments</i>
<i>SB3000</i>	AirPrime	Mar-01	Palm					x		x	x	x		Module for handspring
<i>T60c</i>	Ericsson	Dec-01			x	x	x		x		x	x		software upgrade to CDMA2000
<i>EC 3000</i>		Dec-99		x										Dual band/dual mode (AMPS)
<i>Audiovox Micro-I</i>	Hanwha	Feb-01		x	x	x		x			x			Dual band/dual mode (AMPS)
<i>Audiovox CDM-3400</i>	Hyundai	Mar-01		x	x	x		x			x			Dual band/dual mode (AMPS)
<i>Audiovox CDM-8900</i>	Hyundai	Provisional		x		x		x			x			Dual band/dual mode (AMPS)
<i>HGT-1000E</i>	Hyundai	Provisional		x		x		x		x	x		x	Dual band/dual mode (AMPS)
<i>PE-2</i>	Hyundai	Provisional		x				x						
<i>TX-20B</i>	Hyundai	Provisional			x	x		x		x	x		x	
<i>TX-25B</i>	Hyundai	Provisional			x	x		x		x	x	x	x	
<i>QCP-2235</i>	Kyocera	Dec-01			x	x		x				x		
<i>QCP-2035</i>	Kyocera	Dec-01		x	x	x		x		x	x			Dual band/dual mode (AMPS)
<i>CDMA-Module</i>	Kyocera	Mar-01						x			x			
<i>QCP-2244</i>	Kyocera	Dec-01			x	x		x				x		
<i>QCP-3035</i>	Kyocera	Dec-01		x	x	x					x			Dual band/dual ode (AMPS)
<i>QCP-6035</i>	Kyocera	Feb-01	Palm			x		x		x	x			
<i>LG-TM210</i>	LGIC	Provisional		x	x	x		x		x	x		x	Dual band/dual mode (AMPS)
<i>LG-TM510</i>	LGIC	Mar-00		x	x	x		x		x	x		x	Dual band/dual mode (AMPS)
<i>LG-TM520</i>	LGIC	Provisional				x		x			x	x		Trimode
<i>LG-TM910</i>	LGIC	Provisional			x	x		x		x	x	x		Trimode
<i>STARTAC 7868W</i>	Motorola	Jan-00		x	x	x		x		x	x		x	Dual band/dual mode (AMPS)
<i>Talkabout T2267</i>	Motorola	Sep-00			x	x		x					x	
<i>Talkabout T8367</i>	Motorola	Mar-00		x				x						Dual band/dual mode (AMPS)
<i>Timeport 270c</i>	Motorola	Mar-01			x	x	x	x						
<i>Timeport P8367</i>	Motorola	Jan-00		x	x	x								Dual band/dual mode (AMPS)
<i>Timeport P8767</i>	Motorola	Oct-00		x	x	x		x		x	x		x	Dual band/dual mode (AMPS)
<i>VI20c</i>	Motorola	Jun-01			x	x		x						

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v2267	Motorola	Oct-00		x	x	x		x			x		x	Dual band/dual mode (AMPS)
3285	Nokia	Mar-01		x		x		x						Dual band/dual mode (AMPS)
5185i	Nokia	Mar-00						x		x	x			
6185	Nokia	Apr-99						x		x	x		x	Fax/Data via software modem
6185i	Nokia	Mar-00			x	x		x		x	x		x	Fax/Data via software modem
6188	Nokia	Jun-99						x		x	x			Fax/Data via software modem
SCH-3500	Samsung	Jun-00		x	x	x		x		x	x		x	Dual band/dual mode (AMPS)
SCH0N150	Samsung	Jun-00			x	x		x						
SCH-T300	Samsung	Provisional			x	x		x						
SPH-M100	Samsung	Provisional						x		x	x			MP3 player, 64MB,
SPH-T100	Samsung	Provisional			x	x		x		x	x		x	
Uproar M100	Samsung	Feb-01				x		x		x	x			MP3 player, 64MB,
SCP-4000	Sanyo	Mar-00		x	x	x				x	x			19/AMPS
SCP-4500	Sanyo	Oct-00				x				x	x			
SCP-5000	Sanyo	Dec-00				x				x	x			Color screen
CPD-510	Sewon	Provisional			x	x					x	x		Also IS-95C compatible
CPD-520	Sewon	Provisional			x	x					x	x		Also IS-95C compatible
SWT-1000	Sewon	Provisional			x	x								
AirCard 550	Serria Wireless	Provisional											x	Wireless card
Audiovox CDM-8000XL	Toshiba	Apr-00		x				x		x	x			Dual band/dual mode (AMPS)
Audiovox CDM-8100XL	Toshiba	Apr-00		x	x	x		x		x	x		x	Dual band/dual mode (AMPS)
Audiovox CDM-8150x	Toshiba	Oct-01		x	x	x		x			x	x		Dual band/dual mode (AMPS)
Audiovox CDM-8200	Toshiba	Provisional		x	x	x		x			x			Dual band/dual mode (AMPS)
Audiovox CDM-9000	Toshiba	Mar-00		x	x	x				x	x			Dual band/dual mode (AMPS)
Audiovox CDM-9100	Toshiba	Jan-01		x				x		x	x			Dual band/dual mode (AMPS)
Audiovox CDM-9100	Toshiba	Nov-01		x	x	x		x					x	Dual band/dual mode (AMPS)
			Percent	48%	63%	79%	4%	79%	2%	50%	73%	23%	27%	

Table 6-2. Feature Details of In-Market CDMA 8/19 Handsets as of December 2001²⁹

This table lists the various handset models supporting the North American CDMA standard with dual bands at 800 and 1900 MHz

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Future Handset Feature Projections

With new 3G technologies starting to rollout throughout Europe first, and then the rest of the world shortly afterward, several projections exist for the number of subscribers for the new technologies. It is expected that WCDMA will launch across the bulk of Western Europe commencing in the first quarter of 2004. The handset vendors, who also typically are also infrastructure suppliers, have a vested interest in the success of WCDMA as many of them are financing the infrastructure rollouts. This vendor commitment to WCDMA will follow with GSM/WCDMA handsets being launched into GSM and W-CDMA markets from 2005 and onward.

Table 6-3 is derived from the EMC projections for future handset functionality supporting the rollout of worldwide 3G services. The current rollout of 2.5G provides an indication of percentage of GSM handset sales that are predicted to incorporate GPRS functionality. Several interesting trends should be noted. First, eventually all handsets are projected to incorporate GPRS functionality, first in Western Europe and Asia, and then worldwide. Second, CDMA 1x is expected to only be supported in handsets sold in the Americas, North America, and Asia/Pacific. Finally, W-CDMA is expected to be sold worldwide, but only will be supported in a maximum of 50% of handsets sold. This is mainly due to competition to existing 2G systems, primarily GSM.

Cellular subscriber forecasts are important to understand the ultimate size of the wireless market. Table 6-4 demonstrates the prediction of the number of cellular subscribers based on several population assumptions. The number of worldwide wireless subscribers is expected to more than double between the end of 2001 and 2005. Some markets will see a 400 to 800% increase in subscribers.

Finally, the increased number of subscribers, new system rollout, and normal handset replacement will result in increased demand for new handsets with advanced features. Table 6-5 predicts handset demand based on EMC's market model and subscriber growth figures presented in table 6-4. Handset demand is expected to almost triple by 2005, and referring back to table 6-3, new handsets will be expected to incorporate a range of advanced features and operating modes.

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GPRS Matrix - Indication of GSM Handset Sales with GPRS Functionality

	2001	2002	2003	2004	2005
<i>Africa</i>	0.5%	15%	50%	75%	100%
<i>Americas</i>	0.2%	15%	50%	75%	100%
<i>Asia Pacific</i>	1%	25%	75%	100%	100%
<i>Eastern Europe</i>	0.5%	15%	50%	75%	100%
<i>Western Europe</i>	1%	25%	75%	100%	100%
<i>Middle East</i>	0.5%	15%	50%	75%	100%
<i>USA/Canada</i>	0.5%	15%	50%	75%	100%

CDMA 1x Matrix - Indication of CDMA handset sales with CDMA 1x Functionality

	2001	2002	2003	2004	2005
<i>Africa</i>	0	0	0	0	0
<i>Americas</i>	0	25%	50%	100%	100%
<i>Asia Pacific</i>	12.5%	75%	100%	100%	100%
<i>Eastern Europe</i>	0	0	0	0	0
<i>Western Europe</i>	0	0	0	0	0
<i>Middle East</i>	0	0	0	0	0
<i>USA/Canada</i>	5%	50%	100%	100%	100%

W-CDMA Matrix - Indication of GSM handset Sales with W-CDMA Functionality

	2001	2002	2003	2004	2005
<i>Africa</i>	0	0	0	10%	25%
<i>Americas</i>	0	0	0	10%	25%
<i>Asia Pacific</i>	0	0	0	25%	50%
<i>Eastern Europe</i>	0	0	0	20%	40%
<i>Western Europe</i>	0	0	0	25%	50%
<i>Middle East</i>	0	0	0	20%	40%
<i>USA/Canada</i>	0	0	0	15%	30%

Table 6-3. Predictions of Handset Sales With 3G Functionality²⁹

This table predicts the future percentage of handsets supporting the GPRS, cdma2000 1x, and WCDMA standards based on EMCs market projections and actual data through June 2001.

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<i>Millions of subscribers</i>	<i>2000</i>	<i>2001</i>	<i>2002</i>	<i>2003</i>	<i>2004</i>	<i>2005</i>
<i>Africa</i>	16.6	29.1	48.7	68.1	84.7	100.2
<i>Americas</i>	63.6	92.7	132.5	170.6	202.2	226.4
<i>Asia Pacific</i>	232.1	330.6	442.1	558.8	666.6	761.4
<i>Europe: Eastern</i>	29.5	45.7	61.8	77.0	90.4	101.9
<i>Europe: Western</i>	260.2	336.4	423.3	488.8	532.5	561.1
<i>Middle East</i>	10.4	15.1	20.1	26.3	33.2	40.3
<i>USA/Canada</i>	116.5	139.1	164.5	190.7	215.6	238.2
<i>World</i>	728.8	988.7	1,293.0	1,580.2	1,825.3	2,029.5

Source: EMC World Cellular Database, October 2001 based on actual figures to end June 2001.

Assumptions:

- Saturation point: Assume that the market can grow beyond 100%. All members of a population have the potential for a single subscription, barring the 0-4 year age group. Half of those falling into the economically active population are assumed to have the potential for a minimum of two subscriptions, one for personal usage, and the other for business usage.
- Half of all households are assumed to have the potential for a cellular-enabled device/application.
- Combining the above assumptions results in a saturation point of 140% of the population base.

Table 6-4. World Cellular Subscriber Forecasts²⁹

Based on EMC's market forecasts and assumptions, this table presents the total worldwide cellular subscriber predictions throughout major cellular regions.

<i>1999</i>	<i>2000</i>	<i>2001</i>	<i>2002</i>	<i>2003</i>	<i>2004</i>	<i>2005</i>
265m	403m	457m	498m	589m	653m	697m

Source: EMC World Cellular Database, October 2001 based on actual figures to end June 2001.

Table 6-5. World Cellular Handset Demand²⁹

Based on EMC's market forecasts, this table predicts the future handset demand for all cellular handsets worldwide.

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SECTION 7: DIFFUSION of SDR TECHNOLOGY

Diffusion in Wireless Industry

Sections 3 and 4 discussed the historical trends of various world wide wireless standards, the migration from 1G to 2G technologies, and the potential migration to 2.5G and 3G technologies. Focusing on the transition from 1G to 2G technologies, several important concepts can be noticed. Using the data in previous sections, the following highlights the market aspects affecting diffusion in the wireless industry.

The discussions in section 4 on the evolution from 1G to 2G technologies shows evidence of the dependence on the industry starting point (path dependence), significant network effects, and also a significant role for gateway innovations. The history of the electric power industry is an example of a network industry with the rotary transformer a device that is thought of as a gateway innovation. This example can be used as an analogy for the dynamics occurring in the wireless industry. All such network industries utilize increasing returns technologies that link their users – physically or otherwise – in a network. This gives rise to positive externalities in the use of the network that typically requires coordinating the selection and operation of many complementary constituent parts.

Multicomponent and multiagent network systems that have been discussed in the management literature did not emerge full-blown in the forms that they have come to assume. Systems such as railroads, electric light and power utilities, and telephone networks should be regarded as both society shaping and socially constructed.⁵⁷ These technologies have been built up sequentially, through an evolutionary process in which the design and operation of constituent components were adapted to the specific technical, economic, and politico-legal circumstances in which new opportunities and problems were perceived. Those perceptions, usually, were formed on the basis of experience acquired through the operation of preexisting systems having some of the same, or analogous functions as the ultimate standardized technology.

The cellular industry is no different in these respects. The industry is certainly dominated by network externalities. The number of users demonstrates increasing returns, especially if we ignore the diminishing returns if the networks become overloaded with too many subscribers. Socio-political forces that determine different standards in different parts of the world shape the network infrastructure. Gateway innovations have been identified in such industries to bridge incompatible systems, especially in the regional context.

First, network effects play an important role in the success of various standards and wireless services in general. The success of the analog AMPS system was due in no small part to the availability of regional roaming capability. Compare this to the numerous other 1G standards in Europe, all of which had much smaller market penetration, and quickly assumed a niche role when the 2G GSM system started to become available throughout Europe. Another good indication of the increasing returns of a network of wireless subscribers is the fact that the number of total wireless subscribers is growing at an exponential rate. This is a potential indication that the value to the subscriber of a wireless network increases as the number of total subscribers that uses the network increases, and potentially as the features of the network improves. It seems that the value determinants are the extensiveness of the network and potentially the other users who use the network.

The differences in technology evolution are due in large measure to different government policies and regional geography in Europe, the United States, and Japan. Three types of government policies influence developments in wireless systems: policies on radio spectrum regulation, approaches to R&D, and telecommunications industry structure. The reasons for the shifts in the above example can be found primarily in changes in spectrum regulation policies adopted in the 1980s. In establishing first-generation systems in the United States in the late 1970s, the FCC regulated four properties of a radio system: noninterference, quality, efficiency, and interoperability. This effect was discussed in the previous section.

However, the path dependency has significant implications for future capabilities of the networks. Increasing return systems have a “founders effect.” Therefore, the state as the system evolves to over time may be determined by the initial state and any decisions made along the way. Incumbent systems can be hard to over turn with AMPS in North America being a prime example.

However, markets can still “tip” toward a standard due to numerous network externalities overturning some founder or first mover effects. A comparison of the European and North American experience follows. Gateway technologies are particularly evident in the North American market. As figure 4-4 highlighted, the individual market share for each 2G standard (CDMA, TDMA, GSM) did not exceed that of AMPS until 2000. This was due in part to the fact that most 2G handsets in the U.S. are dual-mode or compatible with both a 2G standard and the legacy AMPS network. This backward compatibility, gateway or translator device, has allowed three separate 2G standards to proliferate in this market, while maintaining and leveraging the strong network of existing AMPS infrastructure. The existence of the analog network has also slowed down diffusion of all 2G standards. Since regional roaming was already enabled by the analog system, users saw few reasons to upgrade to digital technology initially. The improved digital voice quality, battery lifetime, and eventually new features, ultimately won over the majority of the cellular subscriber market. In late 2001 the AMPS only subscribers are decreasing, and few new subscribers are operating primarily only on the AMPS network.

Commercial wireless technologies have followed divergent evolutionary paths in different parts of the world. Strong contrasts are evident in the transition from first-generation cellular systems to second-generation systems in the United States and Europe. At first a single U.S. system was used for analog cellular communications, AMPS, and every cellular telephone in the United States and Canada could communicate with every base station. By contrast, European users were faced with a complex mixture of incompatible analog systems. To maintain mobile telephone service, an international traveler in Europe needed up to five different telephones. The situation was reversed by second-generation systems. Now there is a single digital technology, GSM, deployed throughout Europe (and in more than 100 countries worldwide), whereas the United States has become a technology battleground for three competitors: GSM (PCS-1900), TDMA (IS-136), and CDMA (IS-95, cdmaOne). These evolution paths were illustrated in figures 4-11 and 4-12.

These evolutionary paths warrant further consideration. First, consider North America whose evolution from 1G to 2G standards was represented in figure 4-11. AMPS was legislated as the regional 1G-standard for North America. As a result, it achieved very extensive geographic coverage in North America. It gained tremendous network externalities in the number of subscribers, as well as associated network hardware – handsets, cellular base stations, and control infrastructure. The second-generation systems of GSM, TDMA, and CDMA are incompatible by themselves. The dominant mode of compatibility is through the legacy AMPS network. In this case, the gateway innovation can be considered the ability, or physical device that allows the

system, to have a dual-mode phone with both AMPS and one of GSM, TDMA, and CDMA. AMPS remains the system with the widest coverage, and as such, dual mode phones support a combination of AMPS and GSM or TDMA or CDMA. There are no dual-mode phones in North American markets without the ability to interface with AMPS networks.

Initially in the rollout of 2G systems, all phones had the ability to communicate over AMPS and the associated 2G systems in North America. However as 2G networks proliferated in major metropolitan areas, less expensive single-mode phones have become available. This phone may only operate on GSM for example, without the capability to interface with the legacy AMPS system. This type of phone may meet the needs of a large set of users who don't roam outside areas with good primary system coverage, and was only feasible after an extensive 2G network was deployed. The successful incremental rollout of 2G in North America required the compatibility or gateway functionality of the AMPS system.

Finally, for the world traveler, the GSM world phone is currently available. Although without capability to operate on 1G networks, it has multiband capabilities to interoperate on GSM networks worldwide. For this user also, the existence of 1G compatibility in North America is less important than being able to be reached worldwide with a single phone number on a single phone. The lack of coverage in certain underserved markets by GSM is less important for this user.

In this context of North American 1G to 2G evolution, the gateway innovation of 1G-2G interoperability has a finite lifetime. The ability to interoperate through the legacy 1G infrastructure was essential to enable the rollout of the multiple incompatible 2G standards, but may become obsolete once, and if, a single standard becomes dominant in the North American market or any one of several standards share the market with wide enough overlapping coverage; enabling seamless regional roaming without a gateway to the legacy system.

As stated earlier, the early dominance of AMPS as a 1G standard helped to ensure the slow migration to 2G technologies in North America. This is partially illustrated by figure 4-13, a plot of the market share of major 1G standards as a percentage of the analog system total market share. As can be seen, AMPS achieved an early lead, surpassing 50% market share in 1985. Due to the tremendous "network effects", a tipping occurred to AMPS in primary markets served by AMPS, installation of AMPS networks in European markets served by protocols with thin subscriber bases, and later, an acceleration to a unified 2G standard in markets that were artificially segmented by 1G standards below critical mass of subscriber base.

Figure 4-14 demonstrates the worldwide market share for 2G standards. Spurred by the numerous 1G standards in Europe, GSM entered the market several years earlier than other 2G standards with 100% market share. Due to regulatory barriers, GSM hasn't faced any competition in Europe. As demonstrated by the data, it has achieved a remarkable dominant share of the worldwide market, and has recently reversed early gains made by the competing TDMA and CDMA standards. Network effects are again tipping the market toward a single GSM standard. However it should be noted that there are still four different frequency bands used throughout the world for GSM systems. These four bands still cause difficulty for the so-called world phone, but it is expected that the natural progression of Moore's Law will provide increased levels of integration to enable integration of these four bands into one handset.

This European experience was different than that of North America. Without a dominant 1G standard, there was little need for a common 1G interface in 2G handsets. 1G markets in Europe were artificially segmented by 1G standards that existed below a critical mass of subscriber base.

In fact, the early 2G handsets did have dual mode capability, but it was typically regional, and many people who needed the coverage of the old 1G network for certain reasons, for example, NMT-450 in mountainous Scandinavia, actually carried multiple handsets – a GSM handset for urban use, and an NMT-450 handset for rural coverage. In Europe, the gateway innovation was regional and transitory. Few handsets sold in Europe (see table 6-2) are now available with anything but GSM functionality. GSM has the most extensive coverage in Europe, making the legacy systems obsolete even on that dimension. This is the one dimension that ensured its success in North America. In this instance, the gateway innovation was very short lived, or perhaps even non-existent. The entity in this case which ensured compatibility was the new 2G network itself, perhaps the strong need for a gateway innovation since the new network was inherently more interoperable, and thus had greater network externalities than the older 1G system.

The beginning of the next evolution in gateway innovations for cellular handsets is becoming apparent. For success, the evolution to 2.5G and 3G cellular networks will need a similar compatibility capability to that which was afforded the 1G to 2G evolution. In Europe, new handsets are beginning to have 3G (WCDMA) functionality capabilities in addition to GSM. The natural evolution to 3G from GSM is to WCDMA (see figure 3-11). In Europe, a gateway innovation is likely to be of higher value than during the 1G to 2G evolution. The widely deployed GSM network satisfies the basic need for people to communicate over a wide area. New 3G networks will meet the needs of a small set of early adopters who value the multimedia and higher data rate capabilities, but even they will require the ability to roam throughout Europe.

However, given the incompatibilities in North America it is likely that a backwards compatibility to AMPS will be needed to be maintained for some time in future 3G networks until either the 3G network achieves wide spread rollout or a 2G network is fully deployed. Given that there are three incompatible 3G systems, if each system independently rolls out a 3G system based on the defined path in figure 3-11, then there will be three incompatible 3G networks in North America WCDMA, cdma2000, and UWC136. Again, a method will be needed to bridge the incompatible network standards within the North American region. It's likely from the analogy with the evolution from 1G to 2G that a gateway innovation back to a "universal standard" technology will be maintained, i.e. AMPS functionality in 3G handsets.

Another vision exists. If the cellular providers in North America recognize the steep cost of rolling out multiple incompatible standards, they may decide to either cooperate, or at least, provide interoperability between systems. Due to GSMs dominant and growing worldwide market position, it seems likely that if one standard would begin to dominant, it might be GSM and the associated 3G technology WCDMA in North America. Indeed, there are signs that this may be happening. For example, ATT wireless recently announce it would overlay one of its TDMA networks with GSM, thus providing itself with an upgrade path to WCDMA in the future. If GSM and WCDMA are the future of Europe, perhaps it would be in North America also. There hasn't been tipping to a 3G standard in North America yet, however GSMs worldwide dominance and recent market gains in North America may tip the 2G markets to GSM in the future. The result would be a future of 3G WCDMA in North America, and as a result, a future of GSM and WCDMA compatible phones, rather than AMPS and a multitude of 3G standards.

The comparison between the North American and European evolution illustrate the path dependence in these network systems. Each starting from different system achieves an end point that may be suboptimal. This story hasn't finished playing itself out yet, and it may be that an optimum point is achieved.

Switching costs in this context implies an instability in the system or a tipping effect. There are several possible outcomes, and they may not be predictable a priori. The outcome depends on random historical events. However, the systems may converge ultimately to a winner take all industry with the winning technology not necessarily the best, but locked in nonetheless.

To summarize the 1G to 2G-evolution experience, there are other types of switching costs that impose lock-in. For example in the wireless industry, phone numbers, billing, subscription, and setup costs are all examples of switching costs. Certain media and network effects must be understood including: network externalities, critical mass, systems competition, lock-in and switching costs, path dependence, increasing returns possible, interconnection dynamics, standard setting: market and policy.

Degree to which the sponsors of alternative and incompatible technological systems may lack complete control over the course of the rivalry among them, owing to the possibility that other parties, seeking to capture the benefits of network compatibility, may be induced to develop adapter, converter, or translator innovations.

Gateway innovations open “gateways” permitting the technical interconnection of system components that would otherwise remain isolated. Gateway innovations generally are not impartial in the influence they exert upon the evolution of a network industry. As shown by David, a “neutral” converter, which opens a “gateway” in two directions, nevertheless can tip the balance of market competition decisively in favor of de facto standardization on one of the alternative technological systems. An example is the rotary converter, a device for transforming direct electrical current into alternating current and vice versa.

There is also recognition that enabling two otherwise incompatible subsystems to function conjointly imposes some costs. These include both fixed costs of installing the converter or translator, or they could appear as variable costs that depend upon how often, and with what speed or accuracy, the linkage or conversion operation is performed.⁵⁸

The benefits of gateway technologies may come mainly in the form of greater network externalities accruing to network users who do not use the particular conversion capabilities that are offered. Specifically, if network externalities render the prospects for commercial adoption by private parties poor or especially uncertain, the profit incentives that otherwise might induce efforts toward the invention and development of gateway technologies, correspondingly, will be diminished. This effect would particularly affect the later adopters of technology, for example, those who use 2G after an extensive 2G network has been implemented.

Handset Diffusion and Dominant Design

Wireless subscribers vary in their needs, wants and demands. There is a subset of users who require or benefit from advanced features, and the demand for services vary by geographic region. There is a group of users who are satisfied with basic services; those whose primary need is the wireless network coverage available. For example, into 2001 the analog subscribers in Asia continue to grow even as the digital subscribers also grow. Many people in the US continue to hold onto their AMPS service, even as dual mode phones supporting AMPS and one of the three 2G standards have become the standard in that market. It seems that for these subscribers the basic service of just being able to make a wireless phone call is adequate. These users could be classified as a late majority in Roger’s technology diffusion model. Also, even though the subscriber base is growing exponentially, total market penetration is below 50% for most

markets, except the UK, which has a penetration of 80% (see figure 4-16). Therefore, there is still a sizeable percentage of the potential population for which a wireless phone does not have an attraction.

Even within the 2G-subscriber population, there seems to be spectrum of needs. Referring to the dominant design discussion in section 5, there are a proliferation of handset models for each market and technology standard. Each technological “niche” has handsets with just a basic set of features, and handsets with more features and available services. Many of the features now being incorporated into handsets, such as SMS messaging, are latent, i.e., users many not know they have the capability, and would not care to use that feature if they knew about it.

Comparing the data for features, there seems to be little correlation between the number of bands supported and the number of models addressing that market niche. Referring to table 5-1, there are 157 models that have CDMA-800 capability, and only 61 models that have CDMA-8/19 capability. However, in the GSM niche, there are 406 models supporting the GSM-8/19 band and only 66 models supporting the GSM-900 band. The need to operate in a dual band environment is much more important currently where GSM is widely deployed, where as CDMA networks operating at 1900 MHz are only recently being deployed. However, referring to table 5-2, there is a group of handsets with only basic features, and one group that have more advanced data and messaging capability. Additionally, some newer models are starting to offer a software upgrade path to the 3G CDMA 2000 standard.

It should be noted that the growth of messaging and data features in handsets mirror the development and use of the Internet. As people become more dependent on the Internet for information, they will demand access to these services in a mobile environment. This is another example of network effects, and also complementary assets. The existence of a broadband infrastructure may drive additional high data rate wireless services in the future.

The preceding discussion was meant to highlight that the wireless industry can indeed be segmented into groups, and it seems that a model such as Roger’s technology life cycle can qualitatively fit the market dynamics fairly well. Innovators, early adopters, early majority, late majority, and even laggards seem to be identifiable in this market. Considering Table 6-1, it would seem that most of the wireless industry would like into quadrant 4, where the users are different and the technology is evolving over time. This model assumes that diffusion is driven by relative risk preferences, social adoption pressure, development of complementary technologies and products, price dynamics, and other competitive dynamics. In addition, there are reductions in costs and increases in benefits due to increased technical evolution.

Implications for 3G

This model of the market provides some insight into the future success of 3G services. For 3G, there are some market characteristics that seem to be very important to its success. First, identifying the lead users (innovators and early adopters) would be of prime concern. These individuals would form the communication network about the product benefits. From the manufacturer or service provider perspective, several items should be addressed based on this market.

Maintaining backward compatibility, and inclusion of multimode/multiband capabilities would enable a handset to capture the widest market share. Backward compatibility allows users to roam on more extensive 1G and 2G networks (for example in rural areas, while 3G networks are

being deployed in urban settings). Additionally, if the capability can be supplied at little additional cost, user complexity, or user risk, then forward compatibility can be supplied for the late adopters, who may not need the advanced functions now, but may appreciate the services in the future as more of their peers adopt the new technology.

The 3G standards bodies should strive for global acceptance, and to some extent, they seem to be following this strategy. Because of the evident network effects and complementary assets, it is important to have any new standard adopted in as many major international regions as possible. The continuing success of GSM, which is the only standard in all major markets worldwide demonstrates this fact, and questions the long-term survival of the US TDMA and CDMA standards. The technological interaction modeling in section 4 highlighted the competitive dynamics in the wireless industry as being pure competition. Therefore, regional standards stand to be eventually displaced by standards offering global portability. Also, as learned from GSM and AMPS, a standard that has exclusive presence in a region, may have a better chance of dominating the worldwide market.

The service providers would need to maximize the initial support for a new standard. This allows the widest subscriber base to enjoy the benefits of the new technology. A wide deployment will quickly make legacy systems obsolete. Also, the handset makers and service providers should maintain rapid technological innovation on features that are focused on the user. By rolling out new features, form-factors, and other service and mechanical innovations, the manufacturers will capture more of the innovators and early adopters for the new services, and help to diffuse existing services to the early majority and late majority segments of the market.

Implications for Software Defined Radios

The need for gateway innovations to support compatibility between a small number of existing and future standards were demonstrated in the evolution from 1G to 2G technologies. However, it was also evident that the innovation needed was typically between one regionally dominant 1G standard and one of several emerging 2G standards. The success of any particular 2G standard was not correlated to compatibility with other 2G standard. The technological interaction model parameters, fitted to historical subscriber data in section 4 in particular, indicated that the interaction between 2G standards were pure competition.

In the 1G to 2G evolution, the gateway innovation had a finite lifetime. Once new dominant technologies gain significant market share, the compatibility with legacy systems became less important, as indicated by the emergence of single mode phones in the markets dominated by 2G systems. For example, few GSM phones include compatibility with a 1G standard, and a greater percentage of phone models for the North American market are providing only single mode functionality, with the benefit of reduced complexity, cost, and increased battery lifetimes. Even in North America where GSM networks have less coverage than competing TDMA and CDMA networks, there are only two handsets in the market with AMPS and GSM dual-mode functionality. Even so, GSM subscribers are still growing in North America, even without widespread coverage outside of urban areas and major highway routes.

Although technically feasible, there is a noticeable absence of handsets supporting multiple 2G standards. Dual mode handsets typically support a legacy system and a 1G system. If users need multiple 2G roaming functionality, it is currently not being addressed by the market – even though it is feasible to add another mode at a small cost of additional cost, size, weight, and

corresponding lower battery consumption. Although feasible, users are not demanding this innovation.

The features that users are demanding are application based. Applications such as simple message services, e-mail, voicemail, and more recently personal management functions are becoming more prevalent, especially in the lead users. As higher data rate services are implemented (2.5G and 3G networks), a flood of new applications requiring the high data rates are expected to be available. Once the basic network infrastructure services their needs, users don't seem to care if their applications are over a TDMA, a CDMA, or GSM network. The same is likely for future 3G networks. The applications that users demand, interact with, and value, are implemented on or on-top-of the network. For example, see layered architecture discussion in section 5. New operating systems on the handsets promise a new set of applications independent of the underlying hardware, or even network infrastructure.

3G handset projections by EMC Consulting presented in section 6 indicate that the 3G functionality supported will be determined by legacy 2G protocol support. For example, a percentage of GSM phones will support WCDMA and GPRS, where as a percentage of future CDMA handsets will contain CDMA 1x functionality. This agrees with the thesis above that the legacy support demanded by users is path dependent. Users just want to be able to operate their applications reliably over the network, in general they care less about wider coverage or service areas. Therefore, although technically feasible, there seems to be little market need for SDR technology.

The collision of the cellular telephony and personal computer industries favors the eventual emergence of a programmable handset as the dominant design for a broad variety of hybrid handheld products. Indeed, handheld phone and PDA operating systems are emerging that will allow for portability of programmable applications. Under the pressure to develop low-cost consumer wireless communications products, two sharply divergent approaches have emerged. Following a more traditional hardware development route, one trend is to compress digital radio technology onto a single silicon chip in order to achieve semiconductor industry economies of scale. The opposing effort seeks to transform radio from its present hardware-dominated status into a technology dominated by digital software. However, the severe constraints on size, power consumption, and constraints imposed by consumer handheld device markets favor hardware air-interface solutions for the foreseeable future.

SECTION 8: SUMMARY

Many commercial communications technologies have their roots in military communications niche applications. Developed under very different organizational, political, and technological design practices, as these technologies move out of the military sector and into the consumer electronics arena, the demands imposed by mass markets are revolutionizing their design practices. Software defined radios, a technology developed under years of military research, face significant challenges in the wireless handset market.

This thesis examined various determinants of success in the wireless market by studying the evolution of past market transitions, selection of appropriate system and product architectures, product market diffusion, and the formation of a product dominant design. The collision of the cellular telephony and personal computer industries favors the eventual emergence of a programmable handset as the dominant design for a broad variety of hybrid handheld products. Indeed, handheld phone and PDA operating systems are emerging that will allow for portability of programmable applications. Under the pressure to develop low-cost consumer wireless communications products, two sharply divergent approaches have emerged. Following a more traditional hardware development route, one trend is to compress digital radio technology onto a single silicon chip in order to achieve semiconductor industry economies of scale. The opposing effort seeks to transform radio from its present hardware-dominated status into a technology dominated by digital software. However, the severe constraints on size, power consumption, and constraints imposed by consumer handheld device markets favor hardware air-interface solutions for the foreseeable future.

In this thesis, the history of the wireless communications industry is discussed and analyzed in detail to illustrate the changes occurring in the subscriber use. In this context, the evolution of the use and management of the network was highlighted. For example, the wireless network was the first in many regional markets where private ownership and competition was fostered, creating an appropriate environment for rapid growth. The way subscribers use their telecommunications devices has also evolved. Small, portable handsets have liberated users from the cord that tied telephones to a geographic location, enabling users to be reached anytime, anywhere. No longer do users call a phone number, instead they call a user – expecting that the phone travel with the owner. Beyond this, mobile cellular offers greater variety of options in terms of features and tariffs.

Aspects of rapid change in the wireless communication industry were highlighted:

- Vigorously expanding demand for wireless products and services;
- Dramatic changes worldwide in government policies regarding industry structure and spectrum management;
- Rapidly advancing technologies in an atmosphere of uncertainty about the relative merits of competing approaches;
- Emergence of a wide variety of new systems for delivering communications services to wireless terminals;
- Profound changes in communications industries as evidenced by an array of mergers, alliances, and spin-offs involving some of the world's largest corporations.

Under these influences, the evolution of 1G to 2G systems has been examined in detail to determine common trends that are likely to repeat themselves during the rollout of 3G systems. Several key market and technological factors that have had a significant influence on the relative success of competing analog and digital wireless standards have been identified. It was argued that the nature of the wireless industry is such that these factors will play a similar role in the competition between competing 3G standards and legacy 2G systems.

Network effects play an important role in the success of various standards and wireless services in general. The success of the analog AMPS system was due in no small part to the availability of regional roaming capability. Compare this to the numerous other 1G standards in Europe, all of which had much smaller market penetration, and quickly assumed a niche role when the 2G GSM system started to become available throughout Europe.

During the evolution to 3G technologies, multi-mode operation will be critical to the success of 3G standards. In order to leverage the network effects of the existing 1G and 2G networks, emerging 3G handsets must maintain compatibility with the legacy networks. This gateway innovation was evident in the success of the evolution from 1G to 2G standards, and is expected to be a prerequisite for future 3G rollout. It should be noted that the management theory for gateway innovations imply a temporary capability until the network can tip to the new standard, and the experience with 1G and 2G also bare this out. Therefore, this backward compatibility will only be needed until 3G can gain wide enough deployment. After that point, users will not be willing to pay the extra costs that such a capability implies.

Path dependency has significant implications for future capabilities of the networks. Increasing return systems have a “founders effect.” Therefore, the state as the system evolves to over time may be determined by the initial state and any decisions made along the way. Incumbent systems can be hard to over turn with AMPS in North America being a prime example. Much of the world evolved from multiple 1G standards to a single 2G standard (GSM). However, in North America, a single 1G standard gave way to multiple 2G standards. As a result, much of the world will likely have 3G networks based on the defined evolutionary path of GSM to WCDMA. Whereas in North America, there will likely be competing 3G standards in the future (WCDMA and cdma2000 1x).

The mode of competition between existing standards and invading standards in the wireless industry, as highlighted by the Lotka-Volterra technological interaction model, has historically been that of pure competition. After a period of transition, the networks in the past have tipped to a finite set of standards, and the same is likely to happen with 3G rollout. This ultimately limits the need for a system that can operate over numerous competing standards to a very short time scale – at a cost that might not be acceptable to most users. This model of competition implies that it is imperative to maximize the number of subscribers who initially support a standard. Correspondingly, it is imperative to maximize the number of manufacturers who initially support a standard.

Pure competition could also indicate that backward compatibility and compatibility with other 2G standards is not very important after a certain critical mass of subscribers and network deployment is achieved. The need for a legacy capability, such as backward compatibility to a 1G network, usually has a finite lifetime. After it's lifetime, it is no longer needed and is eliminated due to its extra expense or complexity. Again, the need for a gateway innovation to bridge incompatible networks is usually transitory and these innovations typically have a finite lifetime.

This pure competition hypothesis implies that the mode of interaction would be similar for the 2G to 3G transition. This implies that competing 3G technologies will compete with each other and the existing 2G networks. During the transition period, it is likely that a gateway innovation is needed to provide a large enough network. However, it is likely that the legacy communication needed is between one 2G and one 3G technology. Based on the pure competition between competing 3G standards, there is less of a need for a compatibility device between multiple 3G standards. However, once a dominant 3G technology is established with a broad enough network to satisfy the needs of most users, the need for the backward compatibility or gateway innovation will not justify its added complexity and cost.

Of course, network effects and first mover advantages are evident in the wireless industry causing difficulty in overturning an existing standard. The competing wireless technologies that gain a critical mass in a market are likely to survive, both regionally and worldwide. To determine the technological winner, the worldwide market may need to be assessed, not just the markets where major regional standards are competing. The model simulation of GSM in the North American market illustrated this. However, markets can still “tip” toward a standard due to numerous network externalities overturning founder or first mover advantages. The North American experience with multiple 2G standard rollouts illustrated this point. Most 2G handsets in the U.S. are dual-mode or compatible of operating with both a 2G standard and the legacy AMPS network. This backward compatibility, gateway or translator device, has allowed three separate 2G standards to proliferate in this market, while maintaining and leveraging the strong network of existing AMPS infrastructure. Since on a worldwide basis GSM will be by far the dominant 2G-technology, it is likely that GSM evolutionary derivatives will be the winning 3G-technologies on a worldwide basis. This could indicate that W-CDMA and cdma2000 derivatives are the likely dominant 3G technologies based on evolution of subscribers from 2G to 3G technologies exclusively.

These market characteristics highlight the need for an interim multimode device to enable capability between 2G and 3G networks. Two solutions are available, the hardware air-interface and the SDR handset. Due to its emergence from the convergence of the cellular phone and the PC/PDA industries, the SDR handset is potentially a disruptive innovation to the current wireless infrastructure value chain. This has created both significant market turbulence and potential opportunities for market incumbents and new entrants. Software defined radio technologies are technologically feasible, however users seem to care more about other features than the infrastructure that the phone operates over. Operating systems and portable applications promise to provide evolving features, even if the air-interface remains in hardware. These additional software based features can be considered the basis for a product platform to address different market niches with the features they value the most.

SDR handsets can enable two distinct functions – reconfigurable air interfaces and reconfigurable applications. Reconfigurable applications are being built into hand-held cellular appliances today, using existing cell-phone and hand-held PC standards. In fact, as the operating system discussion illustrated, this application functionality is a reality currently, and is just beginning to capture market share. The telecommunications architecture is structured to provide for such innovations as applications running on the upper layers of the system architecture.

Reconfigurable air interfaces will require further developments in both hardware and software technologies. Moore’s law will continue to provide increased hardware integration, allowing greater functionality to be embedded in hardware. This may be the most efficient means to provide multimode functionality if needed. However, this same technological progression will allow of SDR programmable air-interfaces, with the added costs of reduced battery life and added

size and weight. Users may not be willing to pay a price for flexibility that may not prove to have any current benefits over the hardware air-interface solution.

Finally, the service providers will not push SDR handset technology. Although, service providers are presented as the most influential group in the wireless value chain in terms of their potential impact on the SDR handset, SDR technology would be disruptive to their value chain. Most service providers would not gain benefit by providing roaming capabilities on other competing networks in their home areas. Many providers are not providing nationwide and international roaming via large deployed networks or service agreements with international partners. For those few individuals requiring worldwide roaming, current GSM or dual-phone systems seem to fill this limited niche.

Although there is a proliferation of advanced features, the current dominant design for a basic phone has few extra features. The basic contemporary handset includes at least one air-interface, a portable power source, a keypad for dialing and controlling the phone, a display to display numbers and messages, all packaged in a plastic case. Handset size and multiple air interface capabilities are the most dominant design elements in terms of determining the commercial evolution of software phone technologies and products. In this light, it seems that users would not be willing to accept SDR technology until it is on par with the dominant aspects of hardware only solution. The software application functionality will be achieved with or without a software air-interface. Additionally, the number of current handset models with more than two bands or modes is much smaller than those with even a single band, indicating that the market needs may be satisfied primarily by the simpler technology. This is likely to remain true even with the rollout of 3G technology.

This thesis has focused on SDR in the handset market. However, there is another application where the technology is beginning to make in-roads. If in the future, networks merge or need to be upgraded to new standards, Software radio architectures not promise to reduce the complexity and expense of serving a diverse customer base, and they also promise to simplify the integration and management of rapidly emerging standards. With software-based radio systems, access points, cell sites, and wireless data network hubs can be reprogrammed to meet changing standards requirements rather than replacing them or maintaining them in parallel with a newer infrastructure. This market is more appropriate for SDR technology than the handset market.

This thesis summarized the likely implementation of SDR handsets in a context including handset dominant design, wireless industry innovation diffusion, increasing economic returns, path dependence, network effects, and gateway innovations. Technological lock-in was discussed, but other types of lock-in that may be appropriate include phone numbers, billing, subscriptions, and setup costs are all examples of switching costs in the wireless industry. There are several ways to overcome technological lock-in in the wireless industry. This thesis has focused on new and better technology and gateways to overcome the network effects. However, convergence of communications infrastructures, such as increasingly interchangeable conduits, networks of networks and increasing interconnection, were not addressed. If the vision of increasing convergence becomes a reality, the network may handle the compatibility issues with the user benefiting from a simpler purpose built handset – optimized for its intended purpose.

APPENDIX A

This section contains the model parameters for the Lotka-Volterra models derived for the 1G- to 2G-market diffusion. This work is based on Pistorius and Utterback work on multimode technological interactions⁵⁹. Model parameters were determined using a least squares approach using the Microsoft Excel solver. A pure competition mode between all technologies was found to provide the best fit to the historical market data. Table A1 is the model fit for worldwide analog to digital evolution. Table A2 is the model fit for United States 1G to three 2G standards. Table A3 is the model fit for world wide 1G to three 2G standards.

a1	0.461638589
a2	2.358178213
s11	-1
s12	-1
s21	-1
s22	-1
c11	3.67E-09
c12	1.03E-09
c21	1.10E-08
c22	1.08E-09

Table A1. Lotka-Volterra Model Parameters Fitted to Worldwide 1G to 2G Historical Market Diffusion Data.

Model was fitted with a least-squares algorithm implemented in Microsoft Excel.
Technology 1 is 1G (analog) and technology 2 is 2G (digital).

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a1	5.568544856
a2	2.156234675
a3	4.155478394
a4	3.308583361
s11	-1
s12	-1
s13	-1
s14	-1
s21	-1
s22	-1
s23	-1
s24	-1
s31	-1
s32	-1
s33	-1
s34	-1
s41	-1
s42	-1
s43	-1
s44	-1
c11	1.06E-07
c12	5.87E-08
c13	8.54E-08
c14	3.25E-08
c21	1.36E-08
c22	2.69E-08
c23	2.19E-18
c24	1.31E-18
c31	1.41E-08
c32	3.25E-18
c33	7.52E-08
c34	1.18E-18
c41	1.45E-08
c42	5.40E-08
c43	4.01E-19
c44	1.15E-07

Table A2. Lotka-Volterra Model Parameters Fitted to U. S. 1G- to 2G-Historical Market Diffusion Data.

Model was fitted with a least-squares algorithm implemented in Microsoft Excel.
Technology 1 is 1G (analog), technology 2 is U.S. TDMA, technology 3 is U.S. CDMA
and technology 4 is U. S. GSM.

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a1	15.71295675
a2	0.945690547
a3	15.20947857
a4	25.75260113
s11	-1
s12	-1
s13	-1
s14	-1
s21	-1
s22	-1
s23	-1
s24	-1
s31	-1
s32	-1
s33	-1
s34	-1
s41	-1
s42	-1
s43	-1
s44	-1
c11	1.66E-07
c12	4.88E-08
c13	3.31E-08
c14	6.67E-09
c21	2.60E-12
c22	6.48E-09
c23	0.00E+00
c24	0.00E+00
c31	3.06E-08
c32	1.65E-14
c33	1.29E-07
c34	3.05E-09
c41	1.34E-07
c42	0.00E+00
c43	1.33E-08
c44	1.13E-08

Table A3. Lotka-Volterra Model Parameters Fitted to Worldwide 1G- to 2G-Historical Market Diffusion Data.

Model was fitted with a least-squares algorithm implemented in Microsoft Excel.
Technology 1 is 1G (analog), technology 2 is Worldwide U.S. TDMA, technology 3 is Worldwide CDMA and technology 4 is Worldwide GSM.

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